Theoretical and Empirical Aspects of Financial Market Volatility: Herding, Contagion and Intervention

D. Sumila Tharanga Wanaguru

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NATURAM PRIMUM COGNOSCERE RERUM

Research School of Economics
College of Business and Economics
The Australian National University
Canberra, Australia

Declaration

Unless otherwise indicated in the text, the content of this thesis is a result of original research and has not been submitted for a higher degree in any other university.

D. Sumila Tharanga Wanaguru
Research School of Economics
College of Business and Economics
The Australian National University
Canberra, ACT 0200,
Australia.

Preface

- A version of Chapter 2 is released as *Carry Trades and Financial Crisis: An Analytical Perspective*, Centre for Applied Macroeconomic Analysis Working Paper No. 33/2011.
- A version of Chapter 5 is released as *Currency Intervention: A Case Study of an Emerging Market*, Centre for Applied Macroeconomic Analysis Working Paper No. 32/2012, and is a joint work with Renée Fry-McKibbin.
- The views expressed in this thesis are those of the author/s and do not necessarily represent the views of the Central Bank of Sri Lanka.

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Abstract

This thesis examines the theoretical and empirical aspects of financial market volatility. Financial markets are essentially volatile. However, excess volatility may impair the smooth functioning of the financial system and economic performance. Volatility that was evident in financial markets during the recent financial crisis, and, even more recently, during the European debt crisis, has attracted renewed interest in studying volatility. The most prominent feature of this crisis was its widespread effects on the financial markets of developed countries, while leaving emerging markets as the success story.

The main objectives of this thesis are twofold. The first is to quantify and investigate the nature of the factors behind the transmission of volatility on and among financial markets during the crisis of 2007–2011, with a special focus on developed countries. Both analytical and empirical modeling approaches are used. The analytical approach in Chapter 2 is built up on the herd behavior of international investors, using the role of carry traders' as a conduit. Particular attention is given to modeling the way in which private signals on margin requirements lead some investors to change their decisions, and how their strategic behavior transmits shocks across countries. Chapter 3 adopts an empirical approach using a latent factor methodology, and aims to explore the transmission mechanisms of the crisis through equity and bond markets over different phases of the crisis of 2007–2011. The factor model in particular specifies contagion channels through cross-country and cross-market contagion linkages, after controlling for other forms of fundamentals through the factor structure.

The second objective of the thesis is to examine whether and how successfully emerging market central banks attempt to shield their domestic currency market from externally sourced financial market volatility through foreign exchange intervention. Two empirical approaches, the generalized autoregressive heteroskedas-

ticity approach in Chapter 4 and the latent factor approach in Chapter 5, are used to explore the significance and effectiveness of foreign exchange intervention using a unique data set of daily intervention obtained from the Central Bank of Sri Lanka.

Overall, this thesis finds strong evidence for the transmission of asset market volatility across developed countries during the crisis of 2007–2011. Through herd behavior and the feedback effects in asset prices and exchange rates, financial markets can be destabilized during crises. Financial market contagion is another significant channel through which the stability in the financial system can be compromised, and several channels of contagion are identified and estimated for different phases of the crisis. However, the relative importance of each contagion channel varies depending on the source asset market and the phase of the crisis. Turning to emerging market responses to periods of global volatility, foreign exchange intervention is found to be an effective policy instrument for shielding against external shocks, as is evident for Sri Lanka. Intervention is aimed to "lean against the wind" to reduce volatility and to accumulate international reserves. The central bank responds to global movements in currency markets when intervening, rather than movements specific to the domestic currency market.

List of Acronyms

AIC	Akaike Information Criterion
ARCH	Autoregressive Conditional Heteroskedasticity
BFGS	Broyden-Fletcher-Goldfarb-Shanno (algorithm)
BIC	Bayesian Information Criterion
BIS	Bank for International Settlements
EGARCH	Exponential Generalized Autoregressive Conditional Heteroskedasticity
GARCH	Generalized Autoregressive Conditional Heteroskedasticity
GED	Generalized Error Distribution
GMM	Generalized Method of Moments
IMF	International Monetary Fund
LM	Lagrangian Multiplier
TGARCH	Threshold Generalized Autoregressive Conditional Heteroskedasticity
UK	The United Kingdom
US	The United States (of America)
VAR	Vector Autoregression

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Chapter 1

Introduction

1.1 Overview

The efficient market hypothesis asserts that prices of financial assets should reflect all available information, and should therefore always be consistent with economic fundamentals (Fama, 1970). However, volatility evident in financial markets has forced economists to re-examine the validity of this hypothesis (Scott, 1991; Malkiel, 2003, 2005; Chiang et al., 2010). This thesis studies the theoretical and empirical aspects of financial market volatility.

Modeling financial market volatility has been a significant area of research, and much work has been done to measure, model and understand the volatility transmission mechanism.[1] Linkages between national currency, stock and bond markets with the markets in the rest of the world, and the speed of the transmission of volatility across markets are the main reasons that volatility is a central focus of financial economics (So et al., 1997; Fleming et al., 1998; Mitra, 2011). The policy interest in this area is clear, as understanding the precise causes and consequences of financial market volatility is essential for designing policies that can effectively reduce such volatility, which in turn has implications for general economic growth and stability.

Financial market volatility increases sharply and spills over across markets during crises (Ivashina and Scharfstein, 2010; Schwert, 2011; Diebold and Yilmaz, 2012). The crisis of 2007-2011 has generated a renewed interest in measuring, modeling and understanding how the volatility in one asset market influences

[1]Poon and Granger (2003) provide a review of the literature.

the volatility of related assets markets, both within and across national borders. Unlike past crises in emerging economies, the recent turbulence of the financial market originated in the core of the world economy—that is, in the United States (US) financial markets. Subsequent concerns regarding the solvency of financial institutions, the availability of credit and the decline in investor confidence led the US crisis to spread to other segments of the global financial system.

The crisis of 2007-2011 is considered the worst crisis since the Great Depression in early 1930s (Crotty, 2009). A notable feature of this crisis is its widespread effects on the financial markets of developed countries (Lane and Milesi-Ferretti, 2010). Although more virulent effects were anticipated, emerging markets are the success story of the crisis (Yap et al., 2009; Arieff, 2010; Collier, 2010; Green et al., 2010). Therefore, it is important to investigate the mechanism of the transmission of volatility across developed countries, and the policy tools used by emerging economies to mitigate the adverse effects of sudden shocks stemming from international financial markets.

The main objectives of this thesis are twofold. The first is to quantify and investigate the nature of the factors behind the transmission of volatility to and among financial markets during the crisis of 2007-2011. A special focus is placed on developed country asset markets. The second is to examine whether and how successfully emerging market central banks are able to shield domestic markets from externally sourced financial market volatility. A focus is placed on foreign exchange markets.

This thesis addresses three important economic concepts with regard to financial market volatility during the crisis of 2007-2011: the herd behavior of international investors, the transmission mechanism of financial contagion, and the effects of foreign exchange intervention. The next Section discusses these specific concepts, while the methodological approaches developed to answer these questions are summarized in Section 1.3. A brief outline of the thesis is provided in Section 1.4.

1.2 Key Objectives

The key objectives of this thesis can be considered in two parts. The first part consists of Chapters 2 and 3, in which the transmission of the financial crisis across international asset markets is studied. From this perspective, Chapter 2 develops an analytical framework to explain how a shock arising in one country transmits to another country, even if there is no interdependence or direct links to the changes in the economic fundamentals in the crisis affected country. Chapter 3 empirically studies the relative strengths of the channels of volatility transmission mechanisms during different phases of the recent crisis, using a model of cross-country and cross-market financial contagion. The second part, which consists of Chapters 4 and 5, empirically studies the effectiveness of foreign exchange intervention, which is often used as an important policy tool in offsetting currency market volatility in emerging economies. This Section discusses these specific objectives of the thesis along the three concepts—herd behavior, financial contagion and foreign exchange intervention.

Herd behavior Herd behavior refers to agents who change their behavior to follow the preference of the majority (Gale, 1996; Smith and Sørensen, 2000). "Rational herding" can occur in situations with information externalities when agents' expectations are swamped by the information derived from observing others' actions. In this thesis, particular interest is placed on developing a model that combines: i) the roles of shocks to the haircut or margin requirements on collateralized assets; ii) strategic behavior of international investors; and iii) feedback effects between asset prices and the exchange rate in the investment recipient country. These three concepts play important roles in triggering financial crises, but have not been combined in the existing literature to explain the transmission mechanism parsimoniously. Chapter 2 of this thesis fills that gap in the literature.

The analytical framework is developed under a popular investment strategy of currency carry trades as the mode of investment. In the case of a sudden shock arising in the rest of the world, investors receive private information that is not perfect. This information leads investors to change their behavior. At its core, the analytical framework attempts to demonstrate how individually rational decisions of investors become irrational collectively, shifting the investment recipient country to a bad equilibrium that creates a crisis.

Financial contagion The financial crisis literature has often claimed that crises threaten the stability of the international financial system. One of the channels through which stability can be compromised is financial market contagion (Allen and Gale, 2000; Caramazza et al., 2000; Dungey et al., 2011). Despite little agreement on what "contagion" precisely means in finance, it is widely accepted that the transmission of shocks may be attributed to additional channels or to unanticipated excessive co-movements that cannot be observed in tranquil periods (Dornbusch et al., 2001; Dungey et al., 2011). These additional channels are often termed as "contagion" (Masson, 1999a,b; Dornbusch et al., 2001; Forbes and Rigobon, 2002; Dungey et al., 2011).

Considering contagion as a residual process as in Masson (1999a,b) and Forbes and Rigobon (2002), an empirical latent factor model is specified in Chapter 3 to examine the effects of contagion during the financial crisis. In addition to investigating the existence of financial contagion, several other important aspects related to the global spread of the crisis are also examined. In this context, this Chapter aims to understand the channels of the contagion transmission mechanism. Motivated by the total duration and the widespread nature of the crisis of 2007-2011, this thesis particularly explores how the contagion transmission mechanisms change throughout the crisis. In other words, it investigates the relative importance of the channels through which the various phases of the crisis are transmitted across markets and across borders. Exploring the changing role of the contagion transmission mechanism in different phases of a crisis is important in the policy context as it allows design of appropriate policy measures. However, little has previously been done in the literature to compare phases of a particular crisis.

Foreign exchange intervention As the spread of the recent financial crisis is different to the crises in the context of emerging markets, it is naturally lending itself to an investigation of the effectiveness of policy instruments leading towards the stability of the external sector of emerging markets. Despite the current debate on the role of monetary policy in the face of the recent crisis, price stability remains the primary objective of monetary policy. This often includes the external value of the domestic currency, particularly for emerging economies. Foreign exchange intervention is one among a wide range of instruments available for central banks to achieve their ultimate purpose of price stability (Bofinger, 2001).

Chapters 4 and 5 of this thesis aim to study the efficacy of foreign exchange intervention by the central banks in emerging economies, based on two main goals of intervention: reducing economic costs associated with exchange rate volatility and accumulating international reserves. The case study is for Sri Lanka. Additionally, Chapter 4 investigates whether the central bank focuses only on a "leaning against the wind" policy to reduce volatility, rather than on a particular exchange rate target. Chapter 5 focuses on the factor structure of the exchange rate volatility to identify its sources, and to examine the economic significance of foreign exchange intervention. Both the non-crisis period and the crisis period are considered in assessing the ability of the central bank to achieve its aforementioned objectives.

1.3 Methodological Approaches

Both theoretical and financial econometric techniques were applied in addressing the issues raised in this thesis. The methodological approaches used are briefly discussed in this Section.

Global game approach The global game approach in game theory is the framework adopted in Chapter 2 to develop an analytical framework for the financial crisis, which is not directly linked to changes in economic fundamentals, but unfolds and amplifies as a result of changes in investors' behavior. The global game methodology has been used to analyze bank-runs and currency crashes driven by investors' herd behavior (Morris and Shin, 1998; Goldstein, 2005). Under the assumption of uniform distribution of noisy signals, the model is solved for the threshold level of the size of the haircut, at which the investors make their decision to roll over or unwind their carry trade positions. The solution is then used to determine the equilibrium level of asset prices and the exchange rate in the carry trade recipient country, as in Shin (2005), and to show how the crisis in one country pushes another country to a bad equilibrium.

Latent factor model The latent factor approach in the tradition of Bekaert et al. (2005), Dungey and Martin (2007) and Dungey et al. (2011) is applied in this thesis: i) to explore the contagion transmission mechanism across financial markets during the crisis of 2007-2011; and ii) to investigate the effects of foreign exchange intervention. The latent factor methodology provides a parsimonious modeling approach that addresses econometric issues such as heteroskedasticity, endogeneity, and omitted variable bias as highlighted in Forbes and Rigobon (2002). Especially, it can be used to model financial linkages when the sizes of these linkages are difficult observe directly. In the latent factor approach, returns on financial assets are expressed as linear functions of latent factors. Importantly, this specification can be used to decompose the volatility of each asset return depending on the role each factor plays in contributing to asset market volatility.

Chapter 3 of the thesis applies the latent factor approach to investigate the transmission mechanisms of the crisis of 2007-2011, linking international asset markets. The model is specified in a way that captures the contagion transmission mechanism over three phases of the crisis: the US sub-prime crisis of 2007-2008; the global financial crisis of 2008-2009; and the European sovereign debt crisis of 2009-2011. Further, different source asset markets are used in each phase of the crisis.

The latent factor specification is again applied in Chapter 5 to model exchange rate volatility with foreign exchange intervention. Taking Sri Lanka as the case study, models are run separately for the non-crisis period, and for the crisis period. In each period, a model for non-intervention days and a model for intervention days are jointly estimated. The factor structure provides a convenient method of identifying sources of currency market volatility by decomposing Sri Lankan rupee/US dollar exchange rate returns. The application of the latent factor approach facilitates an assessment of the economic significance of the effects of intervention.

Exponential GARCH methodology Chapter 4 empirically tests the asymmetry in foreign exchange markets with foreign exchange intervention on the basis of GARCH models initiated by Engle (1982) and Engle and Bollerslev (1986). The GARCH specification is applied because of its ability to capture the effects of intervention on the conditional mean and volatility of exchange rate returns in a parsimonious structure. This model can be specifically used to identify whether the Central Bank of Sri Lanka has been successful in achieving its objectives of intervention—that is, to reduce exchange rate volatility and accumulate international reserves.

Using Sri Lanka as the representative country, this Chapter investigates the efficacy of foreign exchange intervention in non-crisis and crisis periods, while exploring whether intervention plays a vital role in shielding against the effects of externally sourced shocks. In this Chapter, GARCH(1,1), TGARCH(1,1) and EGARCH(1,1) models, which are specified to represent the economic fundamentals and the asymmetries of the foreign exchange market in Sri Lanka are compared. The EGARCH(1,1) model is found to be the most appropriate model that fits the data. The main advantage of the EGARCH specification, proposed by Nelson (1991), is that it does not require restrictions to be imposed to ensure non-negativity in the variance, even if negative variables or parameters are included in the variance equation.

1.4 Thesis Outline

The remainder of the thesis is structured as follows. Chapter 2 analytically explains the transmission of the initial effects of the crisis through unwinding of carry trades, which are driven by sudden changes in investors' behavior. Chapter 3 empirically investigates the spread of financial contagion across the developed country asset markets during the crisis. Chapter 4 examines the effectiveness of foreign exchange intervention emerging economies, assessing whether the central bank has been successful in achieving its short- and medium-term objectives of intervention. Chapter 5 extends this analysis by further investigating to identify the sources of exchange rate volatility with and without foreign exchange intervention, and to assess the economic significance of the effects of intervention. Both Chapters 4 and 5 are based on the experience of the Central Bank of Sri Lanka. Finally, Chapter 6 concludes the thesis by revisiting the research questions and summarizing the main findings. This Chapter also discusses some policy implications and offers suggestions for possible future research.

Chapter 2

Carry Trades and Financial Crisis: An Analytical Perspective

2.1 Introduction

Many countries have experienced inflows of foreign exchange driven by the carry trade during the last decade. Countries such as Australia, Iceland, New Zealand and South Africa are among them. The currency carry trade is a speculative financial operation that consists of an investment in a high interest rate currency, such as the Australian dollar or the Icelandic króna ("the investment currency"), financed by borrowing in a low interest rate currency, such as the Japanese yen or the Swiss franc ("the funding currency"). This strategy is based on the underlying motivation of exploiting profit opportunities presented by the persistently low cost of funds in one market segment combined with high returns in another, and possibly also by exchange rate variations.

The greater vulnerability to financial crises in the context of a sudden unwinding of carry positions is a vexing issue for the carry trade economies. One explanation given for this observation is investors' herd behavior. Herd behavior is the tendency for individual carry traders to mimic the actions of a larger group.[1] Herd behavior highlights the possibility that changes in international investors' behavior act as a channel of transmitting the market turmoil across financial markets and across national borders. As explained by Calvo and Mendoza (2000), in the presence of information asymmetries, the cost of gathering information

[1] See Bikhchandani and Sharma (2000) and Cipriani and Guarino (2005) for an overview of the theoretical and empirical research on herd behavior in financial markets.

specific to the investment recipient country could lead to herd behavior, even if investors' make rational decisions. Dividing investors into two groups, namely informed and uninformed, they suggest that uninformed investors find it less costly to follow the actions of informed investors. Therefore, if informed investors move to withdraw investment from the recipient country, unformed investors also tend to follow them, resulting in capital flight.

Carry traders' actions towards taking precautionary hoarding measures under imperfect information in distress situations play a major role in transmitting a shock to the investment recipient country. Carry traders, such as banks or other financial institutions, require capital to structure a carry trade in another country, and usually borrow money from each other at a low interest rate, often using high yielding securities as collateral. The value of this collateral may exceed the amount of cash deposited in exchange for the collateralized asset. The difference between the market value of the security and the collateralized asset is called the "haircut". When there is a financial distortion, currency traders receive private signals about the impact of such a shock on funding constraints: this takes the form of an increase in the size of the haircut (Gorton and Metrick, 2009).

The main goal of this Chapter is to provide a theoretical explanation for currency bubbles and crashes, using the role of carry traders as a conduit. Special interest is placed on understanding the transmission of shocks across developed country financial markets during the initial stages of the crisis of 2007-2011. In this Chapter, carry traders are assumed to be uninformed noise traders, whose decisions are irrational in the sense that their behavior does not necessarily depend on such an optimization behavior. Noise trading can lead to herd behavior, as relatively uninformed investors tend to imitate the behavior of other investors. In the presence of a financial crisis, investors imitating each other can burst a speculative bubble.

The model developed in this Chapter integrates several strands of the finance and game theory literature. In particularly, this Chapter contributes to the existing literature by i) extending the theoretical framework of feedback effects between asset prices and exchange rates as presented in Shin (2005); ii) integrating the concepts of strategic behavior across currency carry traders, or the global game approach in Morris and Shin (1998) and Goldstein (2005); and iii) the haircut applied to collateral discussed by Gorton and Metrick (2009) and Gai et al. (2011). The proposed model parsimoniously explains how a liquidity shock in one country induces a severe crisis in another country.

This model explores the view that pecuniary externalities amongst carry traders generate a unique equilibrium path with endogenous causes for financial crises. After introducing small exogenous noise, this model shows that a liquidity shock in the form of a shock to the size of the aggregate haircut leads both the asset prices and the exchange rate in the carry trade economy to decrease sharply. Liquidity shocks influence the behavior of carry traders in two ways. First is the direct effect. A shock to the aggregate haircut increases premature liquidation by some carry trades, inducing a sale of assets, thus driving down both asset prices and the exchange rate in the carry trade recipient country. Second is the strategic effect. As the withdrawal of funds by some carry traders raises the cost for the other carry traders in the market, an increase in the haircut leads them to foreclose their positions, following the herd. This foreclosure leads the investors in the carry trade recipient country to sell even more of their illiquid assets. As a consequence, asset prices and the exchange rate may decrease more than proportionately to the withdrawal of funds, triggering a financial crisis.

A comparative static analysis shows that a negative shock to the interest rate differential also has the potential to trigger a liquidity crisis in the domestic market and amplify a financial crisis in the carry trade recipient country. The policy implications suggests that the interaction between the size of the haircut, information and investors' behavior has the potential to destabilize carry trades, creating a financial crisis. Therefore, in addition to setting up adequate supervisory and regulatory mechanisms, it is important to control the extent of currency and maturity mismatches of financial institutions in order to prevent the adverse effects of sudden capital flights.

The rest of this Chapter is structured as follows. Section 2.2 gives the motivation to the study by drawing out the circumstances surrounding the recent carry trade collapse in Iceland. Section 2.3 relates this Chapter to the existing literature. Section 2.4 develops the model. Section 2.5 establishes the equilibrium asset price and the exchange rate in the carry trade country, using the equilibrium outcome of the global game among carry traders. Section 2.6 analyzes how an exogenous liquidity shock and a shock to the interest rate differential affect the equilibrium in the carry trade recipient country. Section 2.7 concludes.

2.2 Motivation

This study is motivated by the stylized evidence on the unwinding of the carry trade of the Icelandic króna in 2008. This event attracted much attention given its alleged role in triggering the financial crisis in Iceland.

Iceland has a history of high inflation, and the Icelandic Central Bank, which adopted inflation targeting in 2001, kept official interest rates at a high level to curb an investment and consumption boom (Aksentic et al., 2008). The effects of raising interest rates by the Central Bank of Iceland in response to high inflation led to a vicious circle of an appreciating exchange rate and further capital inflows (Plantin and Shin, 2010). The behavior of the interest rate differential and the nominal exchange rate of the króna against a selection of major currencies are depicted in Figures 2.1 and 2.2.

The unwinding of carry trades dramatically increased in Iceland, following the US sub-prime crisis. As carry traders called back their positions in Iceland, Icelandic banks not only had to sell their assets at fire sale prices, but also had to repay their foreign loans even when the foreign currencies were surging in price. Repatriation of foreign currencies made the króna weaker, and in addition, the interest rate differential between the króna and other currencies decreased as the Icelandic Central Bank cut its official interest rate in order to stimulate the economy. Finally, the currency bubble in Iceland burst as the Icelandic banking system collapsed and a large fraction of the business sector became insolvent, resulting in a severe financial crisis.

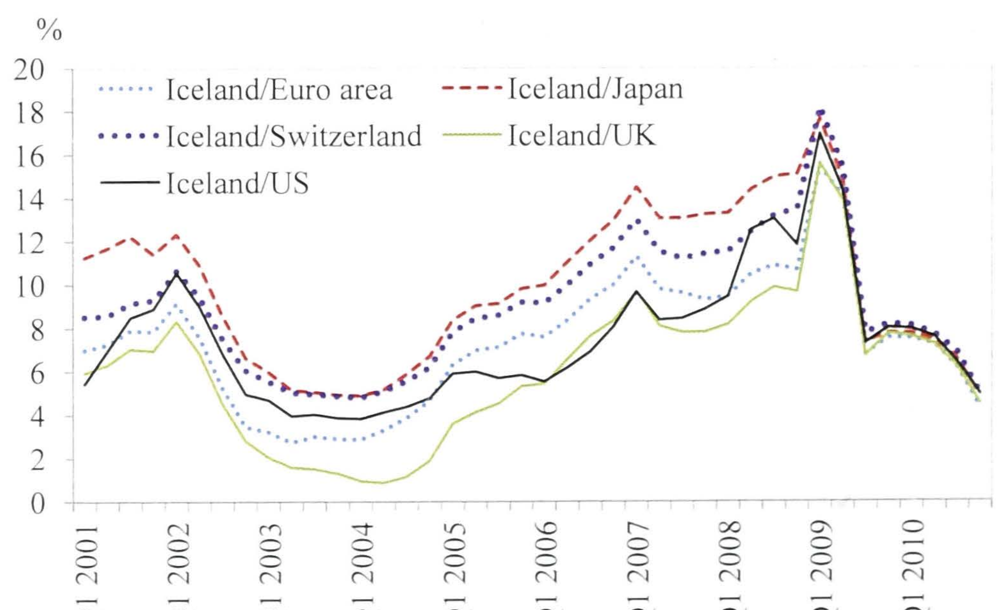


Figure 2.1: Selected Quarterly Interest Rate Differentials for Iceland, 2001 to 2010. Notes: Interest rate differentials are calculated based on the 3-months interbank LIBOR rates (source: Datastream).

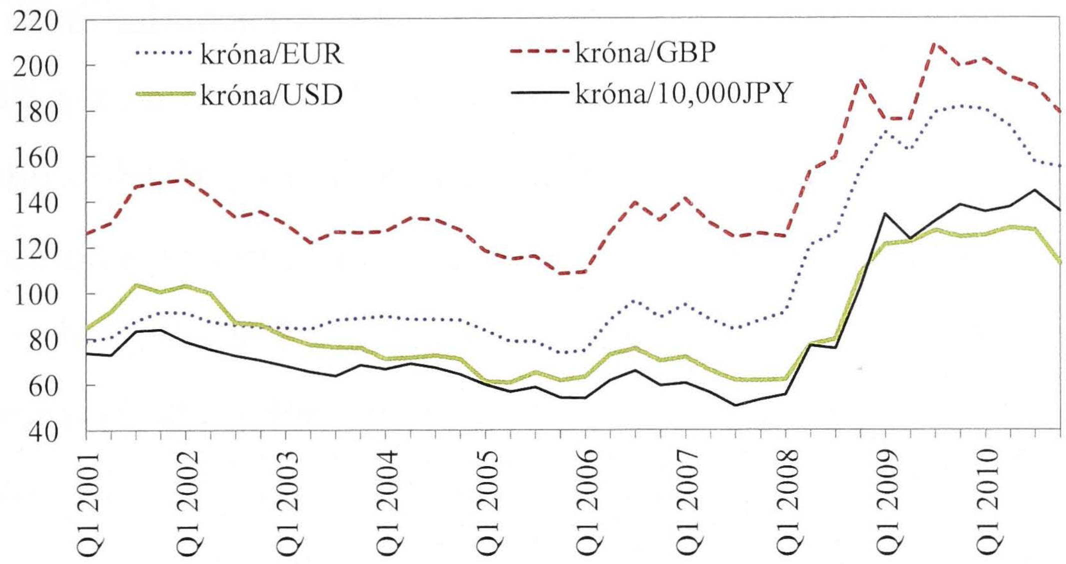


Figure 2.2: Selected Quarterly Exchange Rates of the Króna, 2001 to 2010. Notes: Exchange rates are depicted against euro, GBP, USD and yen (source: Datastream).

2.3 Literature Review

This Chapter unifies three strands presented in the literature: i) liquidity and dynamics of arbitrage by capital or margin-constrained speculators; ii) static coordination games with private information (global games); and iii) the balance sheet approach to financial crisis.

The literature on liquidity and dynamics of arbitrage by margin-constrained carry traders shows that how shocks can be amplified, and result in a financial crisis when liquidity evaporates. Traders provide market liquidity, and their ability to do so depends on the margin constraint (or the haircut) applied to collateral. This concept is clearly documented in Gorton and Metrick (2009) and Gai et al. (2011). Increases in the size of the haircut are reflected in the withdrawals from the securitized banks. The haircut on securities used as collateral reflects the market risk of the collateral. As Shin (2005) explains, if assets are marked-to-market, there is a potential for endogenously generated financial distress that leads to a collapse of asset prices, as well as the exchange rate.

Brunnermeier and Pedersen (2009) explore the extent to which the capital and margin requirements of carry trades depend on the liquidity of assets, and the important role played by liquidity constraints in amplifying financial shocks. Similarly, Kiyotaki and Moore (1997) argue that small shocks can result in large effects because of the role of collateral. A shock that lowers asset prices lowers the value of collateral, leading to a decline in net worth and less ability to borrow. Consequently, asset prices further decline leading to further decline in the value of collateral in a downward spiral. The existing literature also indicates episodes of fire sale pricing, and even destabilizing price dynamics as a result of a negative shock that tightens speculators' margin constraints (Kyle and Xiong, 2001; Xiong, 2001). However, whether the amount an investor can borrow against securities can be used as given is still debatable. For example, Kiyotaki and Moore (1997) and Geanakoplos (2010) present two different views regarding this particular issue.

The literature on the theoretical aspects of the global games with incomplete information is drawn on the type space of a player is whole determined by their own actions, the actions of others and noisy signals about the underlying state. With strategic complementarities, global games often have a unique equilibrium, as small noise in players' perception of the game's payoffs makes the game dominance solvable (Morris and Shin, 2001). Morris and Shin (1998) use the method of global games based on the theory developed by Carlsson and Van Damme (1993), to show that non-common knowledge holds a unique equilibrium, depending on the value of fundamentals. Applying the global game approach in the context of bank runs, Goldstein and Pauzner (2005) solve for threshold values of switching strategies for both bank depositors and for foreign creditors. Plantin and Shin (2010), recently explore a unique equilibrium that exhibits the classic pattern of the investment currency appreciating for extended periods, followed by sharp depreciations.

Angeletos and Werning (2006) and Hellwig et al. (2006) have argued that if private information is aggregated in a large market, the global game approach may fail and the model may be characterized by multiple equilibria. However, Plantin and Shin (2010) justify the application of the global game approach in the context of foreign exchange markets for two reasons. First, the assumption of sequential trades better describes a "decentralized over-the-counter market" such as the foreign exchange market. Second, as the equilibrium uniqueness does not rely on the presence of insiders with accurate private information, the distinction between private and public information is immaterial, thus appropriate in the case of foreign exchange markets (Plantin and Shin, 2010, p.7).

The third strand of literature on which this Chapter draws on how the balance sheet position of the recipient country is affected as investors pull back their positions, leading to a financial crisis. According to this approach, investors observe performances of their investments, and if there is a uncertainty on the liability side of the balance sheet of the recipient country, they may decide to foreclose the investments. The recipient country then has to repay its loans in the foreign currency. This induces a fire sale of illiquid assets and depreciates the exchange rate. This idea of balance sheet approach goes back to third generation models of currency crises (Chang and Velasco, 2001; Edwards and Frankel, 2002). Shin (2005) shows how this feedback effect of market prices, the so-called "liquidity black holes", leads to foreclose investments, creating twin crises; a currency crisis and a banking crisis. Morris and Shin (2004) have also developed a formal model to capture this phenomenon.

2.4 The Model

The first step of the model employs the global game framework to identify the threshold level of the aggregate haircut size, where the actions of carry traders are strategic complement. This threshold level of the aggregate haircut at which the carry traders make their decision to roll over their investment is then incorporated in the feedback model of market prices to identify the equilibrium asset prices and the exchange rate in the investment recipient country in Section 2.5. In setting up the model, the US dollars is used to represent the funding currency, and the Icelandic króna to represent the investment currency. That is, the model assumes currency carry traders borrow in US dollars at a low interest rate and invest in Iceland in order to exploit the interest rate differential.

In the model, the economy consists of two types of players: i) currency carry traders investing in Iceland who usually take the form of financial intermediaries. There are multiple entities of this type in the economy; and ii) a single Icelandic commercial bank. The carry traders are identified as a continuum of risk-neutral investors with unit mass. Each carry trader holds some amount of wealth (an endowment) to transform or invest to produce a stream of returns (Gai and Trivedi, 2009). In this model, it is assumed that each carry trader borrows US dollars from another carry trader at a zero nominal interest rate ($r = 0$), and invests in Icelandic kròna assets at a nominal rate of $r^* > 0$.

The model is a three period static model where periods are given by $t = 0$, 1 and 2. The order of events in the economy leading to a liquidity crisis is

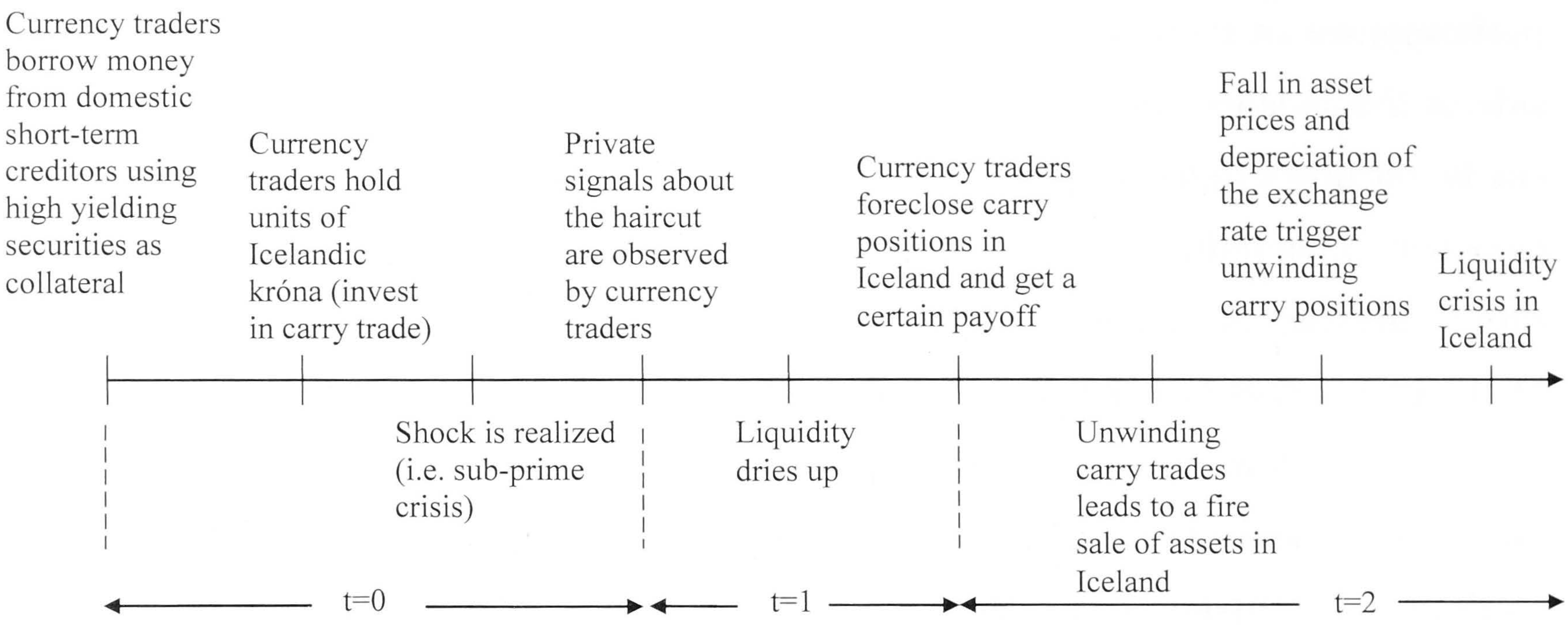


Figure 2.3: The Order of Events in an Economy Leading to a Liquidity Crisis.

depicted in Figure 2.3. Carry traders structure their carry trades in period $t = 0$. That is, they hold some amount of Icelandic kròna assets. Once the sub-prime shock is realized, carry traders receive private signals about the haircut. At the end of period $t = 1$, each trader decides whether or not to roll over their funds in Icelandic kròna assets until the end of period $t = 2$, based on the liquidity condition of its respective balance sheets. If the carry traders decide to foreclose at the end of period $t = 1$, they only receive some portion of the expected amount, which is less than the amount they would receive if they roll over when all the other carry traders continue to do so. However, they receive nothing if they mistakenly decide to roll over when all the others pull back their investment.

The return on an investment in Icelandic króna ($\phi_1(e)$) financed by borrowing in US dollars is denoted by:

$$\phi_1(e) = \frac{R}{e_0} e_1 - \Delta e, \tag{2.1}$$

where, $R = (r^* - r) = r^*$ is the interest rate differential between Iceland and the US. The return on investment is adjusted by the exchange rate e defined as units of króna per US dollar. Thus, a high value of e corresponds to a weak króna. The depreciation of the investment currency is $\Delta e = \frac{e_1 - e_0}{e_0}$. The key assumption here is that the net return to investment increases with the appreciation of kròna/dollar exchange rate.

Tables 2.1 and 2.2 present the compositions of the balance sheets of a representative carry trader and the Icelandic commercial bank, respectively. The total liabilities of the carry trader i (L_i^T) are comprised of retail deposits (L_i^d), short-term borrowing (L_i^{sr}), and capital (L_i^k). The total assets of the carry trader i (A_i^T) are comprised of mortgage backed assets (assets which can be used as collateral) (A_i^m), Icelandic króna assets (A_i^{kr}), and fully liquid assets such as cash and government bonds (A_i^l). These fully liquid assets can be used as collateral to obtain financing for investment, without the risk of a haircut.

Table 2.1: Representative Balance Sheet of Carry Trader i, in US Dollars.

Assets		Liabilities	
Mortgage backed securities	A_i^m	Retail deposits	L_i^d
Kròna assets	A_i^{kr}	Short-term borrowing	L_i^{sr}
Liquid assets	A_i^l	Capital/Net wealth	L_i^k

Table 2.2: Simplified Balance Sheet of an Icelandic Commercial Bank, in Kròna.

Assets		Liabilities	
Domestic assets ($1 \times p$)	A_{ice}^p	Domestic liabilities	L_{ice}^d
		Foreign liabilities	L_{ice}^D

The total liabilities of the Icelandic commercial bank (L_{ice}^T) are comprised of domestic liabilities (L_{ice}^d), and foreign currency liabilities (L_{ice}^D) which is equal to $e \sum A_i^{kr}$. The total assets of the Icelandic commercial bank (A_{ice}^T) are comprised of 1 unit of domestic assets (A_{ice}^p) and 0 units of foreign assets, where p is the asset price.

Carry traders are assumed to be uninformed noise traders who have no information other than the price reflects information of informed investors. Further, it is assumed that carry traders always try to maximize their investment in carry trades, knowing that there is a risk of early foreclosure. Traders need capital to structure carry trades in Iceland. When carry traders buy securities, they can use these securities as collateral to borrow against. However, they cannot borrow the entire market value of the security. Thus, carry traders finance the difference between the market value of the security and the collateralized asset (the haircut) by other sources of funding.

The model assumes that the amount invested by the carry trader i in the Icelandic commercial bank by way of the carry trade is A_i^{kr}. This investment is financed by short-term borrowing from other domestic carry traders using mortgage backed securities (A_i^m) as collateral, along with their own capital. It is assumed that the aggregate haircut associated with A_i^m to obtain finance for a carry investment is denoted by h. No haircut risk is applicable when liquid assets A_i^l are used as collateral for financing purposes. At the same time, the model allows for the possibility of an individual lender-specific haircut, h_i. Therefore, the maximum amount of short-term borrowing that can be obtained by the carry trader using A_i^m as the collateral asset is:

$$(1 - h - h_i)A_i^m, \tag{2.2}$$

where h_i, $h \in (0, 1)$. The remainder, $(h + h_i)A_i^m$, should be financed by the carry trader with its own capital. From the balance sheets of the two key players, it is clear that $\sum A_i^{kr} = (L_{ice}^D)/e$. The model assumes that the carry trader can use the Icelandic króna assets they hold, A_i^{kr}, as collateral to raise funds. These assets are also subject to the same aggregate and idiosyncratic haircuts. Therefore, the maximum amount of funding that the carry trader can obtain using kròna assets as collateral is $(1 - h - h_i)A_i^{kr}$.

Haircuts in the economy are determined by the participants in the market and are subject to change (Gorton and Metrick, 2009). The extent of funding available to a carry trader is determined by the variations in the value of the haircut, and varies as the value of the haircuts fluctuates. The variations in the haircut depends on the amount of funding available to a lending institution, as the haircut determines the maximum permissible leverage ratio of the borrower (Adrian and Shin, 2011). For example, if the haircut is 2 percent, the carry trader can borrow only 98 dollars for 100 dollars worth of securities, that is, the carry trader has to invest 2 dollar worth of equities. The maximum leverage ratio in this case is 50. However, if the haircut increases to 4 percent in the case of an adverse shock hitting the economy reducing the value of assets, the carry trader must either sell assets or raise more equity to finance the gap. The permitted leverage ratio now halves to 25. A consequence of this is that the carry trader must either raise new equity by doubling the equity or reduce leverage by selling half of the assets or do a combination of both (Adrian and Shin, 2011).

Haircuts are associated with funding constraints. The more carry traders borrow in US dollars from the other carry traders in the market, the more relaxed the funding constraint, as the margin (or the haircut) drops. If a carry trader invests in Iceland, the cost of borrowing for the other carry traders decreases. This encourages the other carry traders to invest in Iceland, causing the price of assets to increase and the value of the kròna to appreciate. Therefore, the funding cost of maintaining the carry trade position depends on changes in the value of collateral in the funding currency (Gai and Trivedi, 2009). The sensitivity of the value of collateral to the flow of funds suggests that traders' decisions are strategically interrelated. The greater the flow of funds into high-yielding Icelandic króna assets, the greater the flow of profit that carry traders can earn, as carry traders create positive externalities for each other when they invest their endowment in such assets.

Let the aggregate haircut h for the carry trader i be a function of the fraction of carry traders who foreclose their investment in Iceland l at the end of period $t = 1$:

$$h = \bar{h} + \gamma l, \tag{2.3}$$

where $\gamma \geq 0$, $\bar{h} > 0$ and $0 \leq l \leq 1$. The parameter γ measures the sensitivity of unwinding carry trades to the aggregate haircut, and therefore the sensitivity to the funding constraint in the domestic market. If $\gamma = 0$, the fraction of carry traders who foreclose their investment in Iceland is insensitive to the funding constraint, and $h = \overline{h}$ is the fundamental or the base value of the haircut. However, if $\gamma > 0$, there are negative network externalities, where the carry trader's decision to roll over its investment in Iceland is dependent on the actions of the other carry traders, thereby decreasing the price of assets. If all the carry traders decide to roll over their funds in Iceland until the end of the period $t = 2$ ($l = 0$), the aggregate haircut is equal to its fundamental value i.e, $h = \overline{h}$. However, if γ is large enough, even a small fraction of carry traders fleeing from Iceland can have a significant impact on the haircut, and thus the funding constraint.

The carry trader's decision on foreclosing carry trades in Iceland basically depends on the liquidity condition of the balance sheet. On the whole, the carry trader will remain liquid in each period provided that the amount of collateral available to raise funds is sufficient to cover the short-term borrowing the carry trader has to repay. The carry trader has to finance the haircut from its own capital given any idiosyncratic liquidity shock M_i. Therefore, the carry trader is liquid if:

$$A_i^l + (1 - h - h_i)A_i^m + (1 - h - h_i)A_i^{kr} \geq L_i^{sr} + M_i. \tag{2.4}$$

As $L_i^{sr} = A_i^m$, simplifying the above equation gives:

$$A_i^l - (h + h_i)A_i^m + (1 - h - h_i)A_i^{kr} - M_i \geq 0. \tag{2.5}$$

Exogenous liquidity shocks, or shocks to aggregate or idiosyncratic haircuts, have the potential to trigger a liquidity crisis for the carry trader i, if that carry trader is unable to raise enough funds to maintain the liquidity condition in Equation (2.5). More importantly, a sufficiently large shock to the aggregate haircut has the potential to trigger widespread liquidity stress, not only among carry traders, but also in Iceland.

If the carry trader does not meet the liquidity condition in Equation (2.5), an action needs to be taken to avoid defaulting on required payments L_{ice}^D. There are few options: the carry trader can increase the interest rate on new liabilities in order to obtain sufficient new funding; liquidate fixed assets in a fire sale; hoard liquidity by withdrawing loans made to the other carry traders; or hoard liquidity by unwinding carry trades in Iceland. The first two options are the least attractive as they may reduce the carry trader's future profitability and weaken its capital position. Thus the carry trader may prefer to withdraw the loans made to the other carry traders, or to unwind carry trades in Iceland.

To keep the model simple, it is assumed that carry the trader i calls back its carry positions in Iceland. As a result of this unwinding, the carry trader will lose a portion of the carry investment. In other words, the carry trader will only get a fraction of the expected amount, which is less than what would be received at the end of period $t = 2$ if the project succeeded. The amount that the carry trader receives due to the foreclosure decision can be stated as a function of the exchange rate change and the interest rate differential:

$$\theta \left[\frac{e_1 - e_0}{e_0} + r^* \frac{e_1}{e_0} \right] A_i^{kr}, \tag{2.6}$$

where $0 \leq \theta \leq 1$ is the foreclosure fraction, e_0 is the exchange rate prevailing at the time the carry trader i invested in the Icelandic commercial bank, and e_1 is the exchange rate at the time the carry trader receives the return on investment in Iceland. Here θ represents the proportionate amount that each carry trader gets from unwinding its position in Iceland. The i^{th} carry trader's liquidity condition with premature liquidation can be written as:

$$A_i^L - (h + h_i)A_i^m + (1 - h - h_i)A_i^{kr} + \theta \left[\frac{e_1 - e_0}{e_0} + r^* \frac{e_1}{e_0} \right] A_i^{kr} - M_i \geq 0. \quad (2.7)$$

The simplified balance sheet of the Icelandic commercial bank given in Table 2.2 shows that $(A_{ice}^p - L_{ice}^d)e_0 = L_{ice}^D = A_i^{kr}$. Simplifying Equation (2.7), and linking with the net worth of the Icelandic commercial bank using the fact that $(A_{ice}^p - L_{ice}^d)e_0 = A_i^{kr}$, the liquidity condition of the carry trader i can be stated as:

$$A_i^L - (h + h_i)A_i^m + \left(1 - h - h_i + \theta \left[\frac{e_1 - e_0}{e_0} + r^* \frac{e_1}{e_0} \right]\right) (A_{ice}^p - L_{ice}^d)e_0 - M_i \geq 0. \quad (2.8)$$

From Equation (2.8), it is clear that the foreclosure fraction θ is also a key determinant of the strength of the amplification of shocks in the model. The lower the value of θ, the larger the shocks that can hit the liquidity condition of the carry trader. In principle, the proportionate amount that each carry trader gets from unwinding its position in Iceland depends on the net worth of the Icelandic commercial bank, and how much liquidity a carry trader needs to raise to meet the liquidity condition. If $\theta = 1$, the carry trader will receive the entire amount invested and the profit earned on that investment without any loss. However, at the other extreme, $\theta = 0$ corresponds to an entire loss of the carry trade and the carry trader will receive nothing from investing in the Icelandic commercial bank. If one large carry trader flees from Iceland, this raises the costs for all the other carry traders, and thus may lead the other carry traders to foreclose their investments in the carry trade country.

Carry traders move into carry trading if and only if they believe $l_1 < l_0$. According to Equation (2.1), carry traders move into carry trading whenever the expected profit is positive. Carry traders invest in Iceland when the interest rate differential is greater than zero ($r^* - r > 0$). Therefore, the net profit is positive when $(e_1 - e_0) < 0$. In other words, the net flow of the carry trade increases if the kròna appreciates. A strong exchange rate implies a higher dollar value of collateral and a lower cost of borrowing, and occurs when $l_1 < l_0$. Thus, carry traders move into the carry trade market in Iceland if they believe that the fraction of carry traders who would flee in the next period will be smaller than in the current period, or that the fraction of carry traders who hold kròna in the next period will be greater than in the current period.

2.5 Equilibrium

This Section establishes the equilibrium asset price and the exchange rate in Iceland, using the equilibrium outcome of the global game among carry traders.

2.5.1 Equilibrium of the aggregate haircut

Noisy signal Suppose that the carry trader receives a noisy signal x_i about liquidity, that is about the aggregate or idiosyncratic haircut, in the face of tightening credit supply in a period of financial market distress. Then:

$$x_i = h + h_i, \tag{2.9}$$

where the noise terms or the idiosyncratic component of the i^{th} carry trader's signal h_i is independent and identically distributed ($i.i.d.$), and has uniform density over the interval $[-\varepsilon, \varepsilon]$. Note that h_i and h_j $(i \neq j)$ are independent, and h_i is independent of h. The common term of the signal h has a uniform *ex ante* distribution. Signals $\{x_i\}$ are also uniformly distributed over the interval $[h-\varepsilon, h+\varepsilon]$, that is, $x_i \sim u[h-\varepsilon, h+\varepsilon]$.

The objective of the carry trader i is to maximize the expected profit. The strategy that the carry trader follows to reach this target is a decision rule that maps each realization of the noise signal x_i to an action, i.e., the roll over decision. The equilibrium of this sub-game is a profile of strategies (Morris and Shin, 2006). Therefore, the strategy followed by the carry trader i based on the information available maximizes the expected profit, as all the other carry traders in the game follow a similar strategy in their own profile. Following Morris and Shin (1998), the model solves for an equilibrium in terms of "threshold strategies", which are strategies where a carry trader has a critical realization x^*. If the realization of x_i is above x^*, then the carry trader i will foreclose investment, and if x_i is below x^*, then the carry trader i will roll over. This implies that there is a threshold level h^*, below which carry traders will continue to invest.

Critical level of the signal (x^*) and the threshold level of the size of the haircut (h^*) The next step involves solving for the critical signal x^*, and the threshold level h^* simultaneously. The mass of carry traders who flee are those with signals to the right of x^*:

$$l = \frac{h + \varepsilon - x^*}{2\varepsilon}. \tag{2.10}$$

Therefore, at the critical state:

$$h^* = \bar{h} + \gamma \left[\frac{h + \varepsilon - x^*}{2\varepsilon} \right]. \tag{2.11}$$

Now there is one equation with two unknowns, h^* and x^*. If the carry trader rolls over the funds in Iceland, the net gain is:

$$\pi_1(e) = \left[(1 + r^*) \frac{e_1}{e_0} \right] - e_0, \tag{2.12}$$

and if the carry trader forecloses, the net gain is only a fraction of $\pi_1(e)$, denoted by $\theta\pi_1(e)$. If the carry trader rolls over when others flee, the carry trader loses everything. Conditional on x, h is uniformly distributed over the interval $[x - \varepsilon, x + \varepsilon]$. Therefore, the expected payoff from rolling over, conditional on getting a signal x is:

$$\pi_1(e) \cdot \frac{h^* - (x - \varepsilon)}{2\varepsilon} + 0 \cdot \frac{x + \varepsilon - h^*}{2\varepsilon}, \tag{2.13}$$

and the payoff from foreclosing is non-random and given by $\theta\pi_1(e)$.

At the switching point x^*, carry traders are indifferent to rolling over and foreclosing. Therefore, at x^*:

$$\pi_1(e) \cdot \frac{h^* - (x - \varepsilon)}{2\varepsilon} = \theta\pi_1(e), \tag{2.14}$$

or

$$h^* - x^* = \varepsilon(2\theta - 1). \tag{2.15}$$

Solving Equations (2.11) and (2.15) gives:

$$h^* = \bar{h} + \gamma\theta. \tag{2.16}$$

That is there is a threshold level of the aggregate haircut. Above this threshold carry traders do not meet the liquidity condition stated in Equation (2.8) and thus unwind carry trades in Iceland, and below the threshold the opposite holds. Equation (2.16) shows that the threshold level of the aggregate haircut is directly proportional to the amount that the carry trader receives at foreclosure at the end of the period $t = 1$. In other words, the threshold level of the aggregate haircut is an increasing function of the marginal cost of the premature liquidation. It is important to note that h^* does not depend on the size of the noise term, ε. The switching point x^* in terms of the threshold level of the margin requirement or the aggregate haircut is:

$$x^* = h^* - \varepsilon(2\theta - 1). \tag{2.17}$$

This implies that:

$$h^* = x^* + \varepsilon(2\theta - 1). \tag{2.18}$$

The net effect of the equilibrium of the global game depends on the interplay between fundamental uncertainty, which is the uncertainty concerning the state of nature h, and strategic uncertainty, which is the uncertainty concerning the actions of other investors. In the limiting case where the carry traders are perfectly informed about the collateral constraint which they face ($\varepsilon \to 0$), the switching point x^* is exactly equal to the critical level h^*. Thus, there is no fundamental uncertainty. However, the strategic uncertainty is unchanged even when the private signals become common knowledge.

Solving Equations (2.16) and (2.17):

$$x^* = \bar{h} + \theta(\gamma - 2\varepsilon) + \varepsilon. \tag{2.19}$$

With sufficiently small ε, the switching point x^* is an increasing function of the cost of premature liquidation. It is also necessary to verify that the switching strategy around x^* is the optimal strategy for one carry trader when used by all the other carry traders. If $x_i > x^*$, fewer carry traders will hold Icelandic kròna assets, indicating an increase in l. Thus the optimal strategy is to foreclose. Conversely, if $x_i < x^*$, the optimal strategy is to move into the carry trade.

2.5.2 Equilibrium asset prices and the exchange rate

The solution for the threshold level of the haircut at which the carry traders take their decision to roll over or unwind their carry trade positions in Iceland can now be used in analyzing how asset prices and the exchange rate in Iceland respond to the liquidity shock in the US using the methodology of Shin (2005). In the presence of a financial market turmoil, informed investors re-balance their portfolio to minimize possible losses. Carry traders get information from informed investors, and adjust their expectations depending on the threshold level of the haircut, h^*. If one large carry trader withdraws from Iceland, the increased cost of holding carry positions leads some other carry traders to withdraw their positions as well. As carry traders' decisions exhibit strategic complementarity, or as the reaction among carry traders is reinforced, they begin to follow the herd. The model in this section attempts to show that due to the strategically complementary nature of this behavior, carry traders' attempt to take the most safe action in the period of financial stress causes the exchange rate of the kròna to depreciate against the US dollar, and the price of illiquid assets in Iceland to fall, leading to a currency crisis.

Decision on foreclosing the carry investment Consider the carry trader's decision. A carry trader now knows the fundamental value of the haircut $\bar{h}$ and the idiosyncratic component of the haircut h_i. Also consider the threshold level of the aggregate haircut in Equation (2.16) obtained by solving the global game. This implies that there is a threshold level of the aggregate haircut h^* above which the carry trader forecloses its investment in Iceland. If h^* is close to $\bar{h}+\gamma l$, the carry trader's liquidity constraint tightens, and thus it tends to pull back the carry positions in Iceland. If all carry traders flee from Iceland, the aggregate haircut reaches the upper level $\bar{h}+\gamma$. At the other extreme, if no one flees, the aggregate haircut reaches the lower limit $\bar{h}$. Therefore, if $h^* < \bar{h}$, the carry trader will certainly roll over funds in Iceland. However, the carry trader flees from Iceland if $h^* > \bar{h}+\gamma$. Therefore, the carry trader remains liquid if $h^* < \bar{h}+\gamma$. When $\bar{h} < h^* < \bar{h}+\gamma$, the carry trader is uncertain about his investment strategy, and the foreclosure decision will be taken depending on the threshold value of the haircut. The relationship between the foreclosure fraction and the haircut is shown in Figure 2.4. The upward sloping portion of the foreclosure curve l is

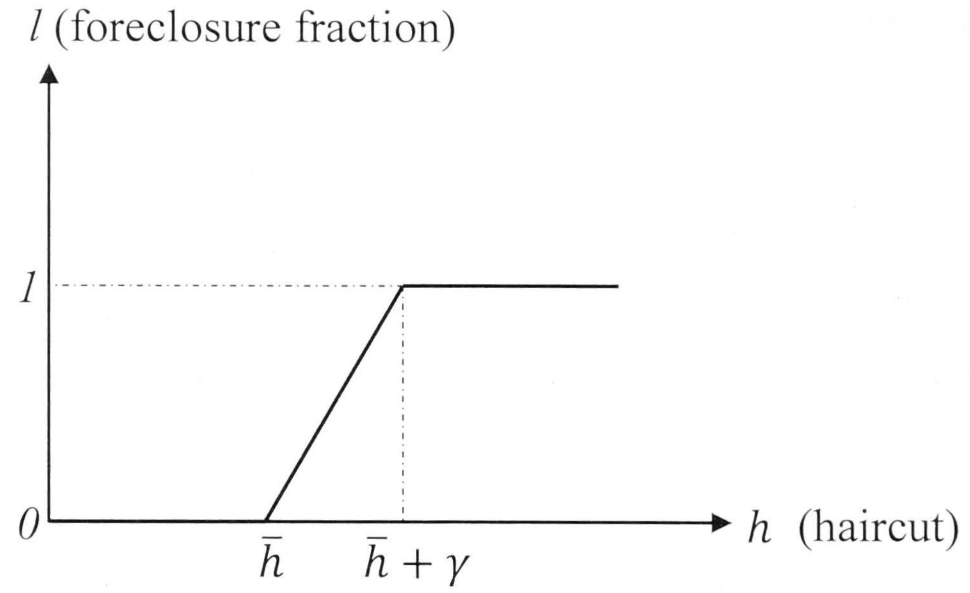


Figure 2.4: The Proportion of Carry Traders Who Foreclose Their Positions.

assumed to be linear and is given by:

$$l = f + ch, \tag{2.20}$$

where f and c are positive constants.

Total sale of illiquid assets If all carry traders continue to invest in Iceland, the total sales of the illiquid assets S by the Icelandic commercial bank is 0. However, carry traders tend to foreclose their positions depending on the threshold value of the haircut when $h^* > \bar{h}$. The Icelandic commercial bank has limited discretion when carry traders refuse to roll over their positions in Iceland. Given the foreclosure decision of some of the carry traders, the Icelandic commercial bank has to raise enough funds to repay the carry traders. The bank has to sell its illiquid assets to meet its funding needs if its net worth is less than some fixed threshold Λ. From the balance sheet, total assets of the Icelandic commercial bank are A^p_{ice}, and total liabilities are $L^d_{ice} + L^D_{ice}$. Noting that $L^D_{ice} = \sum A^{kr}_i$, the Icelandic commercial bank sells its illiquid assets if $A^p_{ice}/e < \sum A^{kr}_i + L^d_{ice}/e + \Lambda$. Denoting $\sum A^{kr}_i = A^{kr}$, the decision rule of the Icelandic commercial bank can be written as:

$$A^p_{ice}/e < A^{kr} + L^d_{ice}/e + \Lambda. \tag{2.21}$$

Assuming that the fixed threshold Λ is uniformly distributed over an interval $[\Lambda_l, \Lambda_u]$, and total holding of illiquid assets by the Icelandic commercial bank is

$\bar{a}$, the total sales S can be expressed as:

$$S = \begin{cases} 0 & \text{if } A^p_{ice}/e > A^{kr} + L^d_{ice}/e + \Lambda_u \\ (f+ch)e/A^p_{ice} & \text{if } (f+ch)e/A^p_{ice} < \bar{a} \text{ and } A^p_{ice}/e < A^{kr} + L^d_{ice}/e + \Lambda_l \\ \bar{a} & \text{otherwise.} \end{cases} \tag{2.22}$$

The amount of assets that should be sold to raise enough funds is determined by the dollar value of illiquid assets held by the Icelandic commercial bank over its foreign currency liabilities to the carry traders. The total kròna value of sale of illiquid assets is $A^p_{ice}S$, and the total dollar value of the sales is $A^p_{ice}S/e$.

Equilibrium asset price Illiquid assets are sold in the domestic market in Iceland. The demand for Icelandic kròna asset is assumed to be linear and negatively sloped (slope$=-b$), and given by:

$$A^p_{ice} = \bar{A}^p_{ice} - bS. \tag{2.23}$$

The equilibrium price of the assets is determined within the domestic market in Iceland. The equilibrium price of the illiquid assets is $\bar{A}^p_{ice}$ in kròna, if there is no foreclosure by the carry traders. If carry traders foreclose their positions, the equilibrium price will be lower than the equilibrium price, $\bar{A}^p_{ice}$. The relationship between the exchange rate e, and the asset price A^p_{ice} is then derived by combining the total sale equation (2.22) and the demand function (2.23):

$$A^p_{ice} = \begin{cases} \bar{A}^p_{ice} & \text{if } A^p_{ice}/e > A^{kr} + L^d_{ice}/e + \Lambda_u \\ \bar{A}^p_{ice} - b((f+ch)e/A^p_{ice}) & \text{if } (f+ch)e/A^p_{ice} < \bar{a} \text{ and } A^p_{ice}/e < A^{kr} + L^d_{ice}/e + \Lambda_l \\ \bar{A}^p_{ice} - b\bar{a} & \text{otherwise .} \end{cases} \tag{2.24}$$

This equation links the exchange rate with the asset price and the relationship is depicted in Figure 2.5.

According to the Equation 2.24 the price of the illiquid assets is a function of the exchange rate and the haircut. When $h^* < \bar{h}$, there is no foreclosure by carry traders, thus no need for selling the illiquid assets by the Icelandic commercial bank. In other words, the Icelandic commercial bank remains liquid. Therefore, in

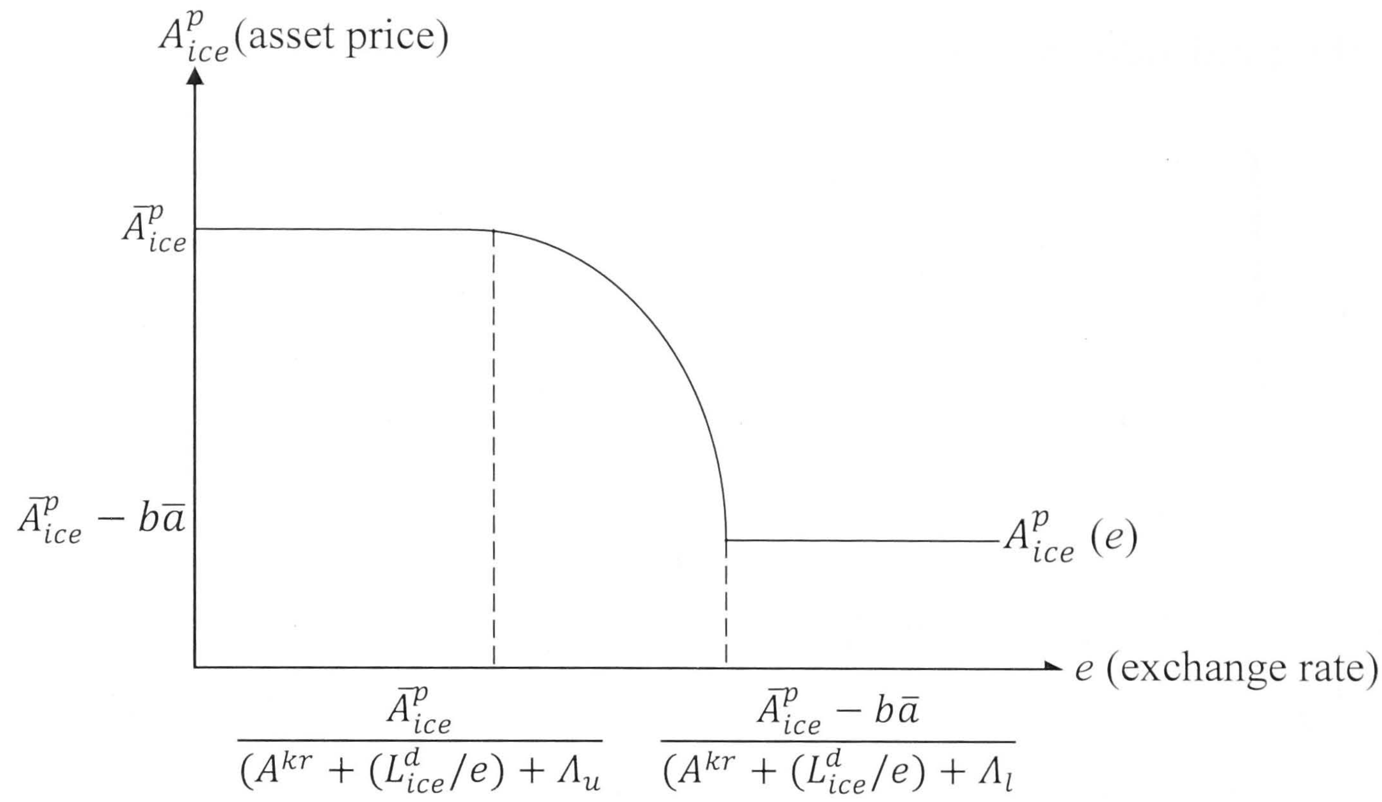


Figure 2.5: Variation of Asset Prices with respect to the Exchange Rate.

the region $A^p_{ice}/e > A^{kr} + L^d_{ice}/e + \Lambda_u$, the sale of illiquid assets $S = 0$. Therefore, the price of the illiquid assets is equal to $\bar{A}^p_{ice}$. However, when carry traders call back their positions as h increases, the Icelandic commercial bank has to sell its illiquid assets ($S > 0$). Consequently, the price of the illiquid assets in Iceland decreases. This, in turn, affects the liquidity level of the carry trader. Putting it another way, a decline in the price of the illiquid assets in Iceland makes it difficult for the carry trader to maintain the liquidity requirements given in Equation (2.8), or to tighten the liquidity constraints or, to increase the haircut. This is due to the decrease in the expected return of the carry trader. If it is difficult for the carry trader to meet their liquidity requirements, it will foreclose more investments, forcing the Icelandic commercial bank to further sell its illiquid assets.

Shin (2005) explained that the increased sale of illiquid assets under such a situation is more than proportionate to the foreclosure by the creditor banks, as the domestic bank has to sell a greater amount of domestic assets to raise the same amount of dollars when the exchange rate depreciates. In this Chapter, increasing the haircut in the US triggers premature liquidation by carry traders, thereby inducing a fire sale and reducing the price of assets in Iceland. Thus, the price of illiquid assets declines faster than expected as the exchange rate depreciates and as the aggregate haircut increases. This decline in price continues until the entire illiquid asset has been sold on the market, that is until $S = \bar{a}$. At this point, $A^p_{ice} = \bar{A}^p_{ice} - b\bar{a}$. This scenario is illustrated in Figure 2.5, and the locally concave portion of the $A^p_{ice}(e)$ curve corresponds to the sharp decline in asset prices when the haircut increases.

Equilibrium exchange rate The relationship between the exchange rate and the asset price can also be derived from the equilibrium condition in the foreign exchange market. Given the foreclosure decision by the carry trader i, the kròna/dollar exchange rate e is assumed to be an increasing function of short-term sale of kròna. The linear short-term demand curve is expressed as:

$$e = \bar{e} + \tau S, \tag{2.25}$$

where $\tau > 0$. If there is no sale of the illiquid assets by the Icelandic commercial bank, the exchange rate is equal to $\bar{e}$, a constant. In other words, if none of the carry traders foreclose their investments in Iceland, $e = \bar{e}$. The elasticity of the kròna/dollar exchange rate, or the degree of short-run illiquidity in the foreign exchange market in Iceland is measured by parameter τ. A larger τ indicates that even a small amount of sale of the illiquid assets leads the exchange rate to depreciate. A consequence of the exchange rate depreciation for the carry trader is a decline in the payoff from premature liquidation.

Given the foreclosure decision in Equation (2.20), a relationship between the exchange rate and the asset price can be derived as:

$$e = \begin{cases} \bar{e} & \text{if } A^p_{ice}/e > A^{kr} + L^d_{ice}/e + \Lambda_u \\ \bar{e} + \tau[f + ch]e/A^p_{ice} & \text{if } (f + ch)e/A^p_{ice} < \bar{a} \text{ and } A^p_{ice}/e < A^{kr} + L^d_{ice}/e + \Lambda_l \\ \bar{e} + \tau & \text{otherwise.} \end{cases} \tag{2.26}$$

Solving the above exchange rate equation, and differentiating with respect to A^p_{ice} gives:

$$\frac{\partial e}{\partial A^p_{ice}} = \frac{-\tau\bar{e}(f + ch)}{[(A^p_{ice} - \tau(f + ch)]^2} < 0. \tag{2.27}$$

Equation (2.27) shows that the reduction of price of the illiquid assets as the Icelandic commercial bank sells assets leads the exchange rate to depreciate.

Equilibrium during a period of financial market stress Following Shin (2005), the equilibrium in the illiquid asset market (2.24) and the equilibrium in the foreign exchange market (2.26) can be plotted together in the (A^p_{ice}, e) space by taking the inverse of the $A^p_{ice}(e)$ denoted by ${A^p_{ice}}^{-1}(e)$. This relationship is depicted in Figure 2.6. The equilibrium asset price and the equilibrium exchange rate is determined at E, the point where the ${A^p_{ice}}^{-1}(e)$ and $e(A^p_{ice})$ curves intersect.

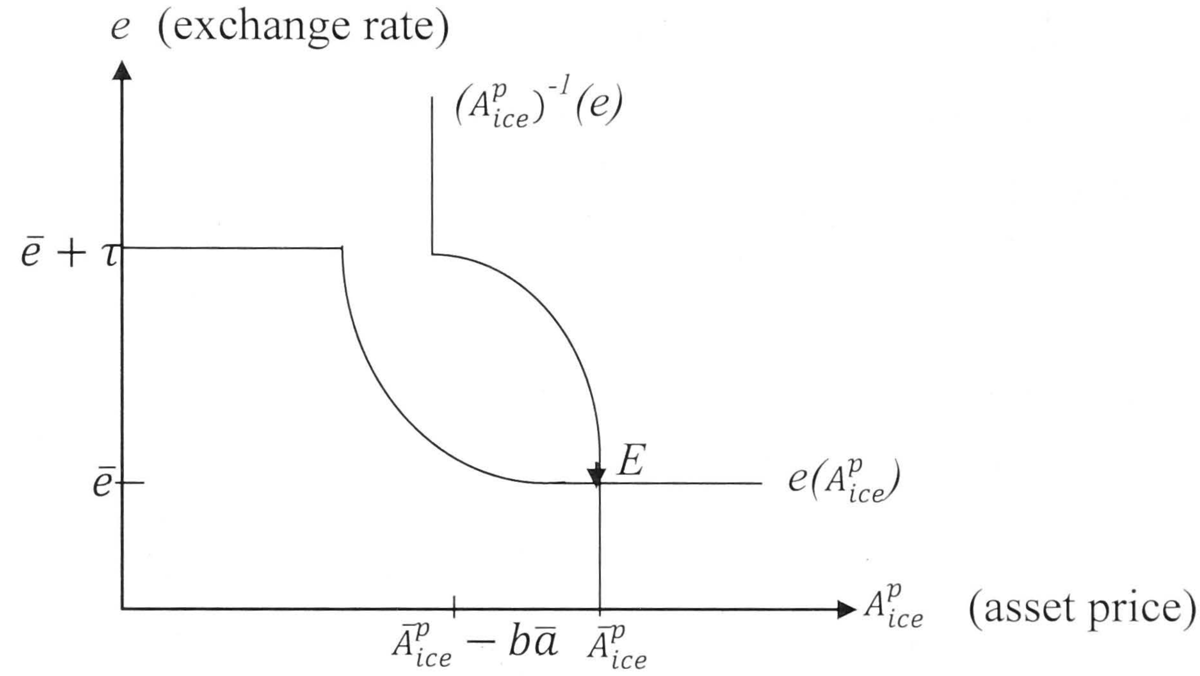


Figure 2.6: Determination of the Equilibrium Asset Prices and the Exchange Rate.

As previously discussed, the margin requirement or the haircut plays an important role in triggering financial shocks. When there is a shock to the haircut, the margin requirement increases, making it difficult for the carry trader to maintain a healthy level of liquidity. Thus, the carry trader pulls back its investment in Iceland. This raises the cost for the other carry traders, and triggers the withdrawal of carry investments. As the sale of the illiquid assets is more than proportionate to the foreclosure, the decline in the price of the illiquid assets, and the depreciation of the exchange rate is sharper compared to the model developed by Shin (2005).

When the liquidity shock or the shock to the aggregate haircut is large enough, the carry trader cannot meet the liquidity requirements. Thus, premature liquidation following the liquidity shock pushes the economy to a situation of distress. If a large fraction of carry traders pull back their investment due to the increase in the haircut ($S > 0$), the asset price decreases. A low asset price induces further selling of the illiquid assets, putting pressure on the exchange rate and tightening the liquidity constraint. This further decreases the asset price. The equilibrium in the periods of financial market stress implies low values for both the exchange rate and the domestic currency. This situation is depicted in Figure 2.7, and the

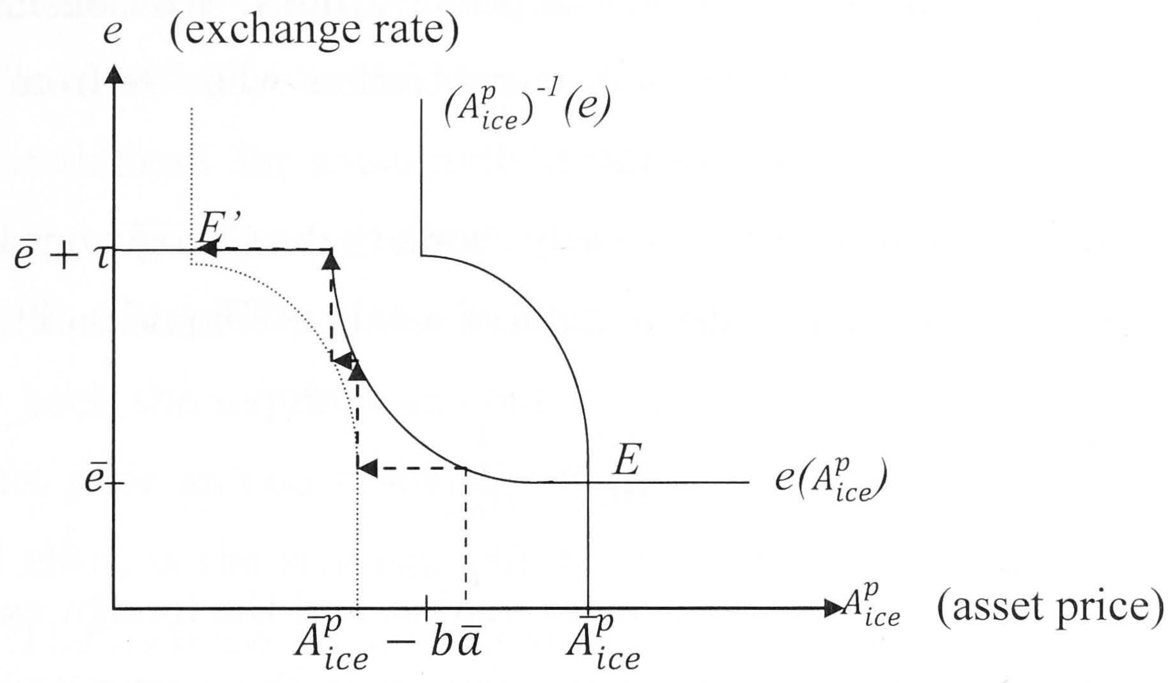


Figure 2.7: Equilibrium Asset Prices and the Exchange Rate During a Period of Financial Market Stress.

new equilibrium point is E'. In summary, the increase in the size of the haircut in the face of an exogenous shock leads carry traders to foreclose carry investments, causing the price of the illiquid assets in Iceland to collapse, and the exchange rate to depreciate sharply.

2.6 Comparative Statics

A set of comparative static results can be used to analyze how a shock affects the equilibrium in the asset and the foreign exchange markets. More specifically, this Section examines the comparative statics effects of i) a liquidity shock or a shock to the aggregate haircut, and ii) a shock to the interest rate differential.

2.6.1 Shock to the aggregate haircut

This Section examines how the foreclosure of carry trades, sale of illiquid assets, equilibrium asset price, and equilibrium exchange rate are affected by a sudden change in the aggregate haircut level. Now consider the foreclosure equation given in Equation (2.20). The fraction of carry traders who forecloses at the end of period $t = 1$ is a function of the aggregate haircut h. Differentiating Equation (2.20) with respect to h gives:

$$\frac{\partial l}{\partial h} = c. \tag{2.28}$$

As c is a positive constant, there is a positive linear relationship between the aggregate haircut and the fraction of carry traders who flee from Iceland in the face of tightened liquidity constraints.

The total sale Equation (2.22) clearly shows that an exogenous liquidity shock, or a shock to the aggregate haircut induces a sale of illiquid assets in Iceland as:

$$\frac{\partial S}{\partial h} = \frac{1}{A^p_{ice}} ce. \tag{2.29}$$

Next, the change equilibria in the asset market and the foreign exchange market in Iceland in response to an exogenous increase in the aggregate haircut applied to collateral is discussed. In this regard, comparative statics of asset price A^p_{ice}, and the exchange rate e with respect to the size of the haircut h are analyzed. Comparative statics for the downward sloping portion of the demand function shown in Figure 2.5 is given by:

$$\frac{\partial A^p_{ice}}{\partial h} = \frac{-bceA^p_{ice}}{(A^p_{ice})^2 + bce(A^p_{ice} - h)}. \tag{2.30}$$

Similarly, differentiating Equation (2.26) with respect to h gives:

$$\frac{\partial e}{\partial h} = \frac{\tau c\bar{e}A^p_{ice}}{[A^p_{ice} - \tau(f + ch)]^2}. \tag{2.31}$$

Equations (2.30) and (2.31) show that:

$$\frac{\partial A^p_{ice}}{\partial h} < 0 \text{ as } A^p_{ice} > h, \text{ and } \frac{\partial e}{\partial h} > 0.$$

Accordingly, an exogenous shock to the aggregate haircut applied to collateral has the potential to decrease asset prices, and to depreciate the króna and the US dollar rate. As the aggregate haircut increases, the fraction of carry traders who foreclose their carry position increases. This induces the sale of illiquid assets in Iceland, pushing down the asset price and depreciating the exchange rate. As a consequence of this exchange rate depreciation, the profit that a carry trader can earn declines. Thus, some carry traders may not meet their liquidity requirements. They will unwind their positions, inducing a sale of assets, and driving down the asset price and the value of the domestic currency even further.

Equations (2.30) and (2.31) together with Figure 2.7 suggest that the marginal increase in the aggregate haircut may lead to the asset price and the domestic currency to decline more than proportionately. This decline reflects two separate effects. The first effect is the direct effect. An increase in the aggregate haircut makes it difficult for some individual carry traders to maintain its liquidity requirement, thus causing them to call back their investment in Iceland. This premature liquidation leads the Icelandic commercial bank to sell its illiquid assets and pay back the required amount in dollars, resulting a decrease in the equilibrium asset price and an exchange rate depreciation.

The second effect is the strategic effect. It arises from the herd behavior of carry traders. The increase in the haircut applied to collateral leads the carry trader to foreclose its carry positions in Iceland. Withdrawal by one carry trader raises the cost for other carry traders in the market, forcing some the other carry traders to flee from Iceland. Due to the strategic complementary nature of carry traders' behavior, they tend to follow the herd. As more carry traders flee from Iceland, the Icelandic commercial bank has to sell more of its illiquid assets. That is, there is an asset fire sale. As the aggregate haircut and sale of assets increase, the asset price in Iceland decreases more than proportionately. At the same time, the exchange rate depreciates as the Icelandic commercial bank converts króna into US dollars. Therefore, an exogenous liquidity shock, or a shock to the aggregate haircut amplifies the widespread liquidity constraints not only among carry traders, but also in the carry trade recipient country.

2.6.2 Shock to the interest rate differential

The carry trade is a popular trading technique in the foreign exchange market that seeks to capitalize on the interest rate differential between currencies. However, if the interest rates of the currencies involved in the carry trade are variable, it creates a risk to the currency carry trader, as any increase in the interest rate of the funding currency or a decrease in the target currency, reduces the expected return on holding carry positions. Therefore, how the change in interest rate differential R affects the equilibrium asset price, and the exchange rate in Iceland needs to be analyzed.

Consider the carry trader's return given in Equation (2.12), where $r = 0$.

Differentiating Equation (2.12) with respect to the interest rate differential R:

$$\frac{\partial \pi_1}{\partial R} = e_1/e_0. \tag{2.32}$$

Thus the carry trader's return increases as the interest rate differential increases, and as long as the exchange rate does not depreciate. With the increase in the interest rate differential, the carry trader's balance sheet strengthens, making it easier to meet the liquidity condition. Therefore, the carry trader will roll over the investment in Iceland. It reduces the cost for the other carry traders for holding the carry positions. Consequently, a lesser number of carry traders will flee from Iceland. If the premature liquidation is reduced, the sale of the illiquid assets by the Icelandic commercial bank decreases, resulting an increase in the price of the illiquid assets in Iceland, while reducing the pressure on króna/dollar exchange rate. This scenario promotes more carry traders to invest in Iceland. On the other hand, a decrease in the interest rate differential causes sudden unwinds of carry trades, creating a financial crisis in the carry trade country.

2.7 Conclusion

In this Chapter, a theoretical explanation was given for the transmission of a financial crisis across national borders through the changes in international investors' behavior. The motivation of the Chapter was drawn from the spread of the financial crisis across developed countries, which began in 2007, and the role of carry traders which was a conduit of the spread of the crisis. A model was developed in which positive externalities among carry traders generated a unique equilibrium with endogenous triggers of currency bubbles and crashes. The analytical framework explained how a shock to the aggregate haircut on collateralized assets caused liquidity in countries with low interest rates to dry up suddenly, carrying the potential for a financial crisis in countries with high interest rates.

This Chapter extended the feedback effects between the asset prices and the exchange rates in the carry trade recipient country developed by Shin (2005) in two ways. First, it introduced the haircut on collateralized assets, as described by Gorton and Metrick (2009), into the model to explain how funding constraints played a major role in unwinding carry trade positions. Second, the model employed the global game method, or the herding behavior of carry traders as in Morris and Shin (1998) and Goldstein (2005) to describe the rationale behind the carry trader's behavior, and also to propose a causal mechanism for the sudden unwinding of carry trades that marked the recent crisis. With these extensions, the model was solved in order to obtain equilibrium in both the asset market and the foreign exchange market in the carry trade recipient country.

The model showed that there is a threshold level of the aggregate haircut, above which carry traders never roll over their investment in carry trade countries. Further, it explored how liquidity shocks or shocks to the size of the aggregate haircut on collateralized assets dried up liquidity among carry traders, forcing them to unwind carry investments and amplifying financial crises in carry trade recipient countries by driving down asset prices and depreciating exchange rates. That is, due to the herd behavior of carry traders' and the feedback effects between asset prices and the exchange rate during the financial crisis, the financial markets become destabilized. The model also showed that a negative shock to the interest rate differential between two currencies had the potential to trigger financial crises in countries with high interest rates.

The possible policy implications highlight the need for financial sector reforms based on the global nature of the crisis. The interactions between the size of the haircut, information available to investors and investors' herd behavior have the potential to destabilize carry trades, creating a vicious cycle which drives down market prices sharply. The results that emerged from this Chapter highlight the necessity of setting up adequate supervisory and regulatory mechanisms, and emphasize the need for controlling the extent of currency and maturity mismatches of financial institutions in order to prevent the adverse effects of sudden capital flights, that is a characteristic of the unwinding of carry trades.

Chapter 3

Financial Contagion and Asset Market Volatility During the Crisis of 2007-2011

3.1 Introduction

Although various explanations may be offered, it is widely accepted that the widespread transmission of financial crises is due to unanticipated excessive co-movements or additional channels that arise only during crisis periods (Dornbusch et al., 2001; Dungey et al., 2011). These additional channels are termed "contagion" in financial economics (Masson, 1999a,b; Dornbusch et al., 2001; Forbes and Rigobon, 2002). Understanding the contagion transmission mechanism of a financial crisis, as well as the vulnerabilities and systemic risk in the global financial system, is important when contemplating financial market, institutional, and macroeconomic reforms to foster a recovery and to prevent such crises in the future.

The volatility that was evident in financial markets during the recent financial crisis, and even more recently during the European sovereign debt crisis, has renewed interest in studying the existence and the strength of contagion across financial markets. A prominent feature of the crisis of 2007-2011 was the quick spread of the effects of the financial market turmoil on and among asset markets in developed countries. Therefore, the objective of this Chapter is to investigate the mechanisms involved in financial contagion across the equity and bond markets of five developed countries: Australia, Europe, Japan, the UK and the US, during the crisis of 2007-2011.

A growing body of literature has attempted to investigate the existence of contagion, and to quantify the strength of financial contagion across markets. Some early contributions are Sharpe (1964), King and Wadhwani (1990), Engle et al. (1990) and Bekaert and Hodrick (1992). Since then, a large body of empirical studies has evolved in this line of study. Dornbusch et al. (2001), Pericoli and Sbracia (2003), Gallo and Otranto (2008) and Dungey et al. (2011) review the literature. The early studies mainly concentrated on the international transmission of shocks for a single asset class (e.g., Eichengreen et al., 1996; Dungey and Martin, 2004; Forbes and Rigobon, 2002; Van Royen, 2002; Favero and Giavazzi, 2002; Dungey et al., 2005). However, cross-market contagion has attracted more attention recently (e.g., Hartmann et al., 2004; Ito and Hashimoto, 2005; Dungey et al., 2006; Dungey and Martin, 2007; Dungey et al., 2011). Notably, Ehrmann et al. (2011) simultaneously modeled four asset classes—stocks, bonds, money markets and exchange rates—in a single framework.

Several methodologies have been used to test for contagion. These may vary from simple statistical methods, such as changes in correlation coefficients and adjusted correlation tests (Forbes and Rigobon, 2002), and outlier tests (Favero and Giavazzi, 2002) to more comprehensive approaches, such as ARCH/GARCH models, Vector Autoregression models (VAR) and latent factor models (Billio and Caporin, 2010; Dungey et al., 2011). Forbes and Rigobon (2002) noted that empirical models should account for heteroskedasticity, endogeneity, and omitted variable problems of contagion. These features are often disregarded in the earlier literature. In an attempt to build an appropriate methodological framework overcoming these issues, many studies try to identify the relative strengths of the variance of country-specific shocks, and global or common shocks weighted by factor loadings (Billio and Caporin, 2010).

The empirical analysis presented in this Chapter is developed using a latent factor approach. The latent factor model is one of two commonly used approaches in identifying common shocks (Billio and Caporin, 2010). The other approach is the VAR model, which selects a set of observable variables to explain common shocks (e.g., Forbes and Rigobon, 2002; Favero and Giavazzi, 2002; Pesaran and Pick, 2007; de Bandt et al., 2010). In the latent factor approach, shocks are explicitly modeled as a set of latent factors, and the model can be specified to allow for potential linkages arising from contagion. Dungey et al. (2011) presents a collection of papers that examine the role of contagion using the latent factor approach. Closest to the current Chapter is Chapter 5 of Dungey et al. (2011).

Studying contagion transmission mechanisms in different phases of a crisis is important, at least for the crises that are characterized by extended durations of financial stress, such as the crisis of 2007-2011. However, little has been done in the literature to compare phases of a particular crisis. This Chapter, not only identifies the existence of contagion, but also explores how the channels of financial market contagion change throughout the crisis, by splitting the total crisis period—from July 2007 to December 2011—into three distinct phases.

In this Chapter, each equity and bond return is specified as a linear combination of common, market, country, idiosyncratic and contagion factors. Two additional channels, which appear only during the crisis are identified as the potential channels of financial contagion linking international asset markets. These two channels are the market and idiosyncratic channels. The market channels transmit the effects of a shock originating in a specific class of asset market globally to individual assets market in all countries. The idiosyncratic channels represent direct contagion links from the source asset market to the other asset markets, nationally and internationally. An important feature of the proposed empirical model is that source crisis markets change during different phases of the crisis, to accurately capture contagion effects at each point in time.

The findings of this Chapter provide several insights. First, asset markets in developed countries are highly susceptible to contagion during all three phases of the crisis. Second, most bond markets are vulnerable to the effects of contagion transmission from equity markets globally, while equity markets are found to be less affected by the transmission of contagion from the global bond market. Third, all of the idiosyncratic contagion channels are at play in transmitting the effects of the crisis of 2007-2011, albeit to different degrees. Finally, and most importantly, no single channel dominates the contagion transmission mechanisms over the three phases of the crisis. This suggests that the channels of contagion transmission vary across asset markets, depending on the phase and the source of the crisis. Overall, this Chapter establishes that the transmission mechanism of financial contagion dynamically evolves even within a crisis.

This Chapter is organized as follows. The order of events during the three phases of the crisis of 2007-2011 is briefly discussed in Section 3.2. The empirical characteristics of the data are analyzed in Section 3.3. A latent factor model of contagion is specified in Section 3.4, and the estimation method is presented in Section 3.5. Section 3.6 discusses the empirical results, and Section 3.7 concludes.

3.2 Chronology of the Crisis of 2007-2011

The sample period used in this Chapter extends from July 01, 2004 to December 30, 2011. In the empirical analysis, the period is first divided into a non-crisis period and a crisis period. The crisis period is again divided into three phases to examine the possible channels of contagion during: i) the US sub-prime crisis, ii) the global financial crisis, and iii) the European sovereign debt crisis.

The non-crisis period is chosen from July 01, 2004 to July 16, 2007. This period was a relatively benign period in the world economy, characterized by low volatility, low inflation and strong economic growth. The phases of the crisis period are:

Phase I: The US sub-prime crisis from July 17, 2007 to September 12, 2008;

Phase II: The global financial crisis from September 15, 2008 to June 30, 2009;

Phase III: The sovereign debt crisis in Europe from July 01, 2009 to December 30, 2011.

The crisis that stemmed from the US sub-prime mortgage and credit market is referred to as Phase I. This phase begins from the date when Bear Stearns in the US officially announced their failure. The sub-prime crisis deepened during the period from mid-2007 to September 2008, and its effects spread in the form of a severe economic downturn. The sub-prime crisis began as a consequence of the complexity of financial innovations in the US financial market, and the failure of financial regulators and credit rating agencies. The crisis was evident by the sharp contraction in liquidity experienced by financial institutions in the US, when rolling over investors' positions. As the concerns over the solvency of financial institutions increased, the crisis spread across other developed countries, such as the UK, during the first year of its development. The nationalization of

Northern Rock bank in the UK is an example of the spread of the crisis into other developed countries (Bordo, 2008; Hodson and Quaglia, 2009).

The second phase of the crisis is dated from September 15, 2008, in line with the collapse of Lehman Brothers in the US. The crisis, which affected developed economies, started to spread globally through all parts of the financial sector following this collapse. The sudden failure of investors' confidence, large liquidation of investments and the collapse of stock markets quickly brought the financial market stress to unprecedented levels. The end date of phase II is in line with the National Bureau of Economic Research (NBER) announcement that the US recession ended in June 2009.

Once the crisis reached Europe, countries in the European region started to experience substantial economic downturns. Emerging as a result of the exposure to unstable fiscal policies, including measures taken to control the depth and the breadth of the initial phases of the crisis and issues specific to countries in this region, fears of a sovereign debt crisis in Europe developed among investors around the world. The intensity of the European debt crisis increased after early 2010, when countries such as Greece, Italy and Spain faced severe problems in refinancing their debts. Even to date, uncertainties are spreading over the European region. Therefore, phase III of the crisis in this Chapter—the period from July 01, 2009 to December 30, 2011—represents the European debt crisis.

3.3 Equity and Bond Data

Contagion across financial markets during the crisis of 2007-2011 is empirically examined by using daily excess returns on equities and bonds for Australia (AU), Europe (EU), Japan (JP), the UK (UK) and the US (US). Excess returns on equity are calculated from equity indices, and are expressed in US dollar terms. Data corresponding to German financial markets are used to represent Europe. This covers the non-crisis period and the three phases of the crisis, as explained in Section 3.2. All of the data are obtained from Thomson Financial Datastream. A detail description of the data used in this Chapter is given in Appendix A.1.

The five countries selected in this Chapter belong to three time zones: Asia-Pacific, Western Europe and the US. Kleimeier et al. (2008) suggested that time zone alignment is required when actual trading hours differ across markets. One-day lagged excess returns on the US assets are used in this Chapter to account for this time zone problem.[1] Daily excess returns on equities $x^s_{i,t}$ are calculated as:

$$x^s_{i,t} = [\ln(r^s_{i,t}) - \ln(r^s_{i,t-1})] - \ln(r^b_{US,t-1}), \text{ and} \tag{3.1}$$

daily excess returns on bonds $x^b_{i,t}$ are computed as:

$$x^b_{i,t} = -n(r^b_{i,t} - r^b_{i,t-1}) - r^b_{US,t-1}, \tag{3.2}$$

where $i = AU, EU, JP, UK, US$, and r^s and r^b are equity indices and bond yields, respectively. $[\ln(r^s_{i,t}) - \ln(r^s_{i,t-1})]$ is the first difference of the natural logarithms of the equity indices and $(r^b_{i,t} - r^b_{i,t-1})$ is the first difference of the bond yields with maturity of 10 years ($n = 10$). Bond returns are calculated as the negative first difference of bond yields times the maturity.[2] Excess returns are calculated by subtracting the returns on the 10-year benchmark US Treasury bond yield ($r^b_{US,t}$) from each series. The percentage excess returns are used in the empirical analysis, and are presented in Figure 3.1. The shaded regions correspond to the three phases of the crisis.

Figure 3.1 shows that the volatility of the excess returns of the assets increases during the total crisis period compared to the non-crisis period. This is also evident from the descriptive statistics of the excess asset returns in the non-crisis and crisis periods as shown in Table 3.1. The standard deviations show that the volatility of the excess equity returns increased by at least 71 percent, while the volatility in the excess bond returns increased by at least 57 percent during the total crisis period, compared to the non-crisis period. Additionally, all the average excess asset returns are positive during the non-crisis period, whereas, except for the UK bond returns, they are negative during the total crisis period.

A comparison of the summary statistics in the three phases of the crisis shows a substantial reduction in the average excess returns of all the equity markets during phases I and II. The standard deviations of the excess equities in all other countries are found to be higher than that of the US during these two phases of the crisis. This shows that equity markets in other countries have been more

[1] One-day lagged excess returns on the US assets are used in this Chapter as no significant change could be observed in the results, even if different lags were used, as suggested by Bae et al. (2003).

[2] See Campbell et al. (1997) for more information about calculation of returns on bonds.

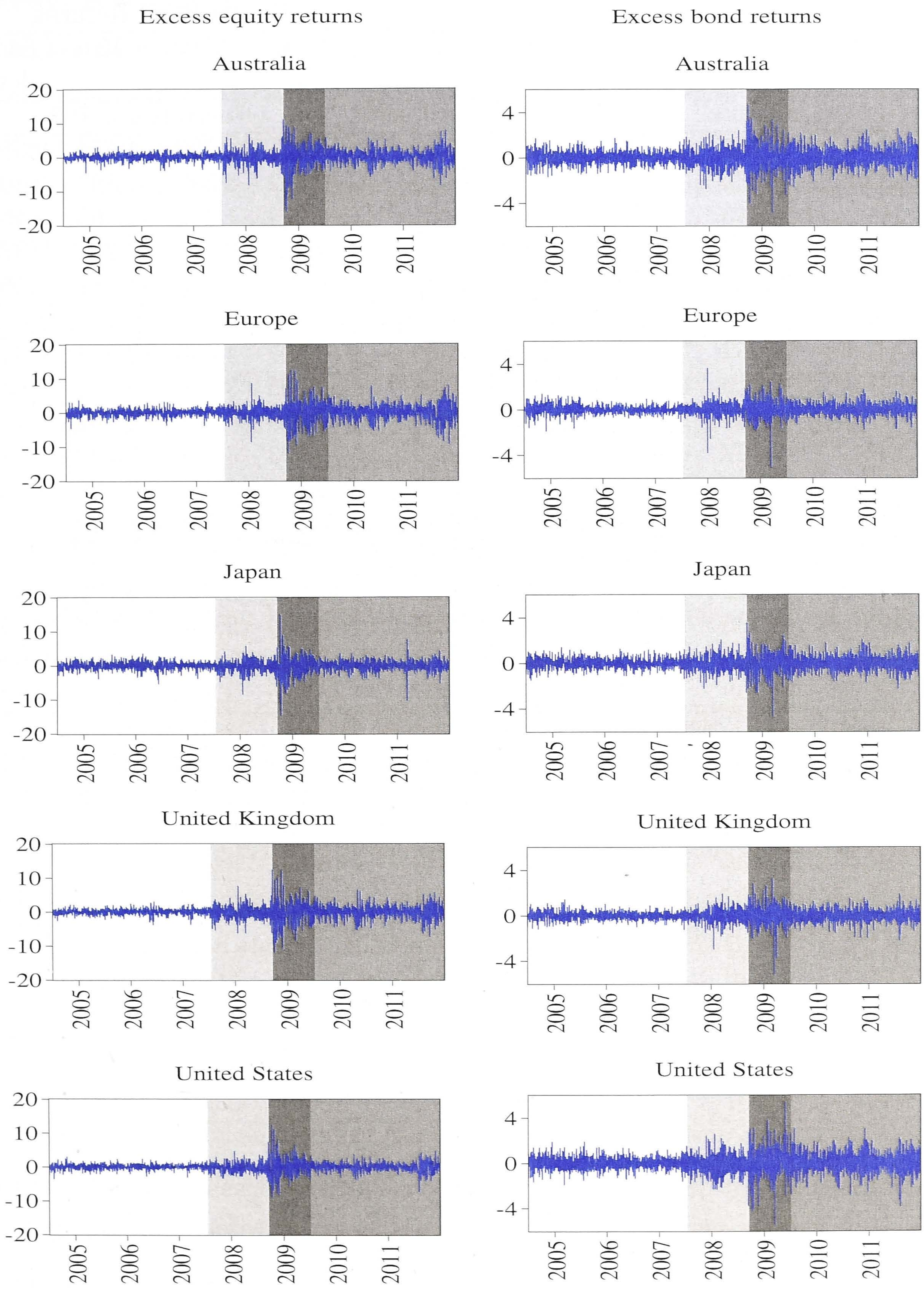


Figure 3.1: Percentage Daily Equity and Bond Excess Returns, Expressed in US dollars, July 2004 to December 2011. Note: The shaded regions correspond, respectively, to the US sub-prime mortgage and credit crisis (July 17, 2007-September 12, 2008), the global financial crisis (September 15, 2008 to June 30, 2009) and the sovereign debt crisis in Europe (July 01, 2009 to December 30, 2011).

Table 3.1: Descriptive Statistics of Excess Equity and Bond Returns (percent).

	Excess Equity Returns				Excess Bond Returns			
	Mean	Max	Min	Std. dev.	Mean	Max	Min	Std. dev.
Non-crisis period: July 01, 2004-July 16, 2007					Observations: 792			
AU	0.107	3.381	-4.484	1.042	0.001	1.703	-1.654	0.579
EU	0.109	3.732	-4.555	1.099	0.002	1.386	-1.893	0.406
JP	0.045	3.529	-5.247	1.151	0.004	1.402	-1.465	0.462
UK	0.076	3.009	-3.699	0.859	0.001	1.415	-1.222	0.373
US	0.042	2.924	-3.469	0.775	0.006	1.889	-1.882	0.567
Crisis period: July 17, 2004-December 30, 2011					Observations: 1164			
AU	-0.052	10.938	-15.888	2.509	-0.007	4.660	-4.802	0.942
EU	-0.060	12.531	-11.783	2.453	-0.003	3.614	-5.062	0.640
JP	-0.054	14.689	-14.603	1.964	-0.019	3.551	-4.702	0.755
UK	-0.067	12.457	-11.850	2.269	0.003	3.269	-5.202	0.680
US	-0.038	12.269	-8.907	1.735	-0.014	5.383	-5.502	1.033
Crisis phase I: July 17, 2004-September 12, 2008					Observations: 304			
AU	-0.151	6.696	-8.236	2.234	-0.027	2.370	-2.755	0.871
EU	-0.122	8.602	-8.559	1.789	-0.030	3.614	-3.791	0.630
JP	-0.135	5.769	-8.333	1.738	-0.030	2.046	-2.218	0.693
UK	-0.160	7.586	-6.195	1.898	-0.014	1.906	-2.944	0.620
US	-0.108	4.631	-3.556	1.407	-0.055	2.564	-2.319	0.897
Crisis phase II: September 15, 2008-June 30, 2009					Observations: 207			
AU	-0.119	10.938	-15.888	4.000	-0.002	4.660	-4.802	1.333
EU	-0.137	12.531	-11.783	3.742	0.031	2.448	-5.062	0.914
JP	-0.054	14.869	-14.603	3.253	-0.002	3.551	-4.702	1.057
UK	-0.166	12.457	-11.850	3.630	0.033	3.269	-5.202	1.015
US	-0.152	12.269	-8.907	2.984	-0.017	5.383	-5.502	1.444
Crisis phase III: July 01, 2009-December 30, 2011					Observations: 653			
AU	0.015	7.659	-8.339	1.961	0.001	2.550	-2.542	0.817
EU	-0.006	7.918	-9.193	2.194	-0.002	1.780	-1.740	0.529
JP	-0.016	7.667	-10.253	1.460	-0.002	2.083	-2.240	0.663
UK	0.008	6.398	-7.166	1.826	0.001	1.890	-2.160	0.566
US	0.031	4.613	-7.256	1.275	0.006	3.083	-3.861	0.932

volatile than the US equity market. Excess equity returns of Australia, the UK and the US resume to being positive in phase III of the crisis. The standard deviations of all excess equity returns during phase III are lower than that of phase II, but are still higher than the non-crisis period.

Although all average excess bond returns are negative during the crisis phase I, Europe and the UK report positive average excess bond returns in phase II. In phase III, except for Europe and Japan, all the other excess bond returns are positive on average. Again, standard deviations of excess bond returns in all three phases of the crisis are considerably larger compared to the non-crisis period. However, as was the case in equity markets, the standard deviations in phase II are higher than those of phase I and III. Similarities that can be identified in the movements in equity and bond markets during different episodes in the crisis highlight the co-movements in financial variables.

All the excess equity and bond returns used in the empirical analysis are demeaned and adjusted for any dynamics. The strategy followed is to use the residuals obtained from a simple 10-variate VAR(1) as the filtered data. The use of demeaned residuals obtained from a VAR analysis is a standard in models of contagion as a control for market fundamentals and cross-market interdependence (Favero and Giavazzi, 2002; Forbes and Rigobon, 2002; Dungey et al., 2011).

3.4 Factor Model Specification

This Section develops an empirical latent factor model of contagion which is built on the framework of Bekaert et al. (2005); Dungey and Martin (2007) and Dungey et al. (2011) to identify the relative strengths of additional transmission channels that link international asset markets during crises. This framework is related to the theoretical model of Kodres and Pritsker (2002). In Section 3.4.1, a latent factor model of excess returns of equities and bonds for the non-crisis period is specified. The non-crisis model assumes that the volatility of excess asset returns can be captured through a "common" factor, which affects all equity and bond markets simultaneously; a set of "market" factors, which affect equity and bond markets separately; "country" factors, which are common to both markets within the same country; and "idiosyncratic" factors, which are specific to each asset market in a particular country. The non-crisis specification is augmented in Section 3.4.2 to specify the model of contagion during the three phases of the crisis, assuming that contagion transmits from additional market and idiosyncratic channels that appear only during the crisis period. All the factors are assumed to be independent stochastic processes with zero mean and unit variance.

3.4.1 Non-crisis model specification

This Section specifies a latent factor model of excess asset returns for the non-crisis period. Denoting the excess return on asset j in country i at time t during the non-crisis period as $x^j_{i,t}$, the model of excess asset returns can be presented as a linear combination of four factors given by:

$$x^j_{i,t} = \alpha^j_i A_t + \beta^j_i B^j_t + \zeta^j_i C_{i,t} + \upsilon^j_i U^j_{i,t}, \quad i = AU, EU, JP, UK \text{ and } US, \quad j = s, b, \tag{3.3}$$

where s and b refers equities and bonds, respectively. Under this specification, the variable A_t represents the common factor that affects all excess asset returns in all countries, but with different parameter loadings for each market in each country. The term B^j_t captures shocks common to asset j, and $C_{i,t}$ is the country factor that represents the effects common to country i. The set of idiosyncratic factors specific to each individual asset in a particular country is given by $U^j_{i,t}$. The loadings of these common, market, country and idiosyncratic factors are given, respectively, by α^j_i, β^j_i, ζ^j_i and υ^j_i. For example, excess returns on the Australian equities can be specified as:

$$x^s_{AU,t} = \alpha^s_{AU} A_t + \beta^s_{AU} B^s_t + \zeta^s_{AU} C_{AU,t} + \upsilon^s_{AU} U^s_{AU,t},$$

and excess returns on the US bonds can be expressed as:

$$x^b_{US,t} = \alpha^b_{US} A_t + \beta^b_{US} B^b_t + \zeta^b_{US} C_{US,t} + \upsilon^s_{US} U^b_{US,t}.$$

3.4.2 Crisis model specification

In this Section, the non-crisis model is extended to specify the factor model of contagion during the three phases of the crisis. Unlike the existing empirical studies, distinct sets of countries are used as sources in different phases of the crisis. Among the countries used in this Chapter, the US, the UK and Europe are most likely to be the sources of shocks. Therefore, contagion is assumed to be transmitted through the US and the UK idiosyncratic equity and bond market channels during the first two phases of the crisis, and through the US and the European idiosyncratic equity and bond market channels during phase III.

The effects from the US, the UK and Europe are not specified simultaneously in a single model in order to avoid practical issues in estimating the model, given the large number of parameters required to be estimated in the complete system. The specification of the model also allows for the market and idiosyncratic parameters to exhibit structural breaks between the non-crisis and crisis periods. The inclusion of structural breaks captures general increases in volatility in asset markets globally and individually. The crisis model is specified assuming that contagion does not transmit through common and country factors.

Model specification for phases I and II of the crisis The US and the UK are considered the source countries when specifying the factor model of contagion for the first two phases of the crisis. In the model, $x^j_{i,t}$ are the excess returns on asset j in country i at time t during the crisis period, κ represents contagion effects, and a *tilde* over the relevant parameter represents structural breaks.

Consider the countries that are chosen as source countries during the first two phases of the crisis; that is, the UK and the US. Excess returns on equity markets of these two countries during phase I and II of the crisis are specified, respectively, as:

$$\begin{aligned} x^s_{UK,t} &= \alpha^s_{UK}A_t + (\beta^s_{UK} + \tilde{\beta}^s_{UK})B^s_t + \kappa^s_{UK,b}B^b_t + \zeta^s_{UK}C_{UK,t} + (\upsilon^s_{UK} + \tilde{\upsilon}^s_{UK})U^s_{UK,t} \\ &\quad + \kappa^s_{UK,US^s}U^s_{US,t} + \kappa^s_{UK,UK^b}U^b_{UK,t} + \kappa^s_{UK,US^b}U^b_{US,t}, \text{ and,} \end{aligned} \tag{3.4}$$

$$\begin{aligned} x^s_{US,t} &= \alpha^s_{US}A_t + (\beta^s_{US} + \tilde{\beta}^s_{US})B^s_t + \kappa^s_{US,b}B^b_t + \zeta^s_{US}C_{US,t} + (\upsilon^s_{US} + \tilde{\upsilon}^s_{US})U^s_{US,t} \\ &\quad + \kappa^s_{US,UK^s}U^s_{UK,t} + \kappa^s_{US,UK^b}U^s_{UK,t} + \kappa^s_{US,US^b}U^b_{US,t}. \end{aligned} \tag{3.5}$$

Excess returns of the UK and the US bond markets are expressed, respectively, as:

$$\begin{aligned} x^b_{UK,t} &= \alpha^b_{UK}A_t + (\beta^b_{UK} + \tilde{\beta}^b_{UK})B^b_t + \kappa^b_{UK,s}B^s_t + \zeta^b_{UK}C_{UK,t} + (\upsilon^b_{UK} + \tilde{\upsilon}^b_{UK})U^b_{UK,t} \\ &\quad + \kappa^b_{UK,UK^s}U^s_{UK,t} + \kappa^b_{UK,US^s}U^s_{US,t} + \kappa^b_{UK,US^b}U^b_{US,t}, \text{ and,} \end{aligned} \tag{3.6}$$

$$\begin{aligned} x^b_{US,t} &= \alpha^b_{US}A_t + (\beta^b_{US} + \tilde{\beta}^b_{US})B^b_t + \kappa^b_{US,s}B^s_t + \zeta^b_{US}C_{US,t} + (\upsilon^b_{US} + \tilde{\upsilon}^b_{US})U^b_{US,t} \\ &\quad + \kappa^b_{US,UK^s}U^s_{UK,t} + \kappa^b_{US,US^s}U^s_{US,t} + \kappa^b_{US,UK^b}U^b_{UK,t}. \end{aligned} \tag{3.7}$$

Excess returns on equities and bonds of the other countries—Australia, Japan and Europe—are specified as:

$$x_{i,t}^s = \alpha_i^s A_t + (\beta_i^s + \tilde{\beta}_i^s) B_t^s + \kappa_{i,b}^s B_t^b + \zeta_i^s C_{i,t} + \upsilon_i^s U_{i,t}^s + \kappa_{i,UK^s}^s U_{UK,t}^s + \kappa_{i,US^s}^s U_{US,t}^s$$
$$+\kappa_{i,UK^b}^s U_{UK,t}^b + \kappa_{i,US^b}^s U_{US,t}^b, \qquad \text{and,} \tag{3.8}$$

$$x_{i,t}^b = \alpha_i^b A_t + (\beta_i^b + \tilde{\beta}_i^b) B_t^b + \kappa_{i,s}^b B_t^s + \zeta_i^b C_{i,t} + \upsilon_i^b U_{i,t}^b + \kappa_{i,UK^s}^b U_{UK,t}^s + \kappa_{i,US^s}^b U_{US,t}^s$$
$$+\kappa_{i,UK^b}^b U_{UK,t}^b + \kappa_{i,US^b}^b U_{US,t}^b, \qquad \text{for } i = AU, EU \text{ and } JP. \tag{3.9}$$

The market factor B_t^j is modeled assuming that increased volatility during the crisis is due to contagion, as well as structural breaks. The effects of structural breaks in the asset markets are captured by $\tilde{\beta}_i^j$. The parameter $\kappa_{i,b}^s$ measures the contagion effects of bond market shocks on each country's equity markets, while the contribution of the contagion effects from the equity market factor to the bond markets is measured by $\kappa_{i,s}^b$. The effects of the idiosyncratic contagion channels from the UK and US stock markets to the other markets are represented by κ_{i,UK^s}^j and κ_{i,US^s}^j, respectively. Similarly, the contributions of the bond market idiosyncratic factors are given by κ_{i,UK^b}^j and κ_{i,US^b}^j, respectively. Finally, $\tilde{\upsilon}_{UK}^j$ and $\tilde{\upsilon}_{US}^j$ are the structural breaks that represent unexpected changes in the UK and US asset markets, respectively, during phases I and II of the crisis.

For simplicity, the set of equations given in Equations (3.4)-(3.9) can be summarized as:

$$x_t = \alpha_A A_t + \Lambda_B B_t + \zeta_C C_t + \Upsilon_U U_t, \tag{3.10}$$

where Λ and Υ contain new factor loadings of the market and idiosyncratic factors after introducing structural breaks and contagion channels.

Model specification for phases III of the crisis The next step is to specify a factor model of contagion for the third phase of the crisis. The same procedure as in phases I and II is applied, however, with two main changes. First, this model assumes that the US and Europe are the source countries. Thus, the UK equity and bond market specifications given in Equations (3.4) and (3.6) are replaced by the European asset market specifications $x_{EU,t}^s$ and $x_{EU,t}^b$, such that:

$$x_{EU,t}^s = \alpha_{EU}^s A_t + (\beta_{EU}^s + \tilde{\beta}_{EU}^s) B_t^s + \kappa_{EU,b}^s B_t^b + \zeta_{EU}^s C_{EU,t} + (\upsilon_{EU}^s + \tilde{\upsilon}_{EU}^s) U_{EU,t}^s$$
$$+ \kappa_{EU,US^s}^s U_{US,t}^s + \kappa_{EU,EU^b}^s U_{EU,t}^b + \kappa_{EU,US^b}^s U_{US,t}^b, \text{ and} \tag{3.11}$$

$$x^b_{EU,t} = \alpha^b_{EU} A_t + (\beta^b_{EU} + \tilde{\beta}^b_{EU}) B^b_t + \kappa^b_{EU,s} B^s_t + \zeta^b_{EU} C_{EU,t} + (\upsilon^b_{EU} + \tilde{\upsilon}^b_{EU}) U^b_{EU,t}$$
$$+\kappa^b_{EU,EU^s} U^s_{EU,t} + \kappa^b_{EU,US^s} U^s_{US,t} + \kappa^b_{EU,US^b} U^b_{US,t}. \quad (3.12)$$

Second, the idiosyncratic UK equity and bond market channels of contagion are replaced by the idiosyncratic European asset market channels for the recipient asset markets. That is, all the idiosyncratic UK contagion channels given by κ^j_{i,UK^s} and κ^j_{i,UK^b} in Equations (3.8) and (3.9) are replaced by κ^j_{i,EU^s} and κ^j_{i,EU^b} for $j = s, b$ and $i = AU, JP$ and UK:

$$x^s_{i,t} = \alpha^s_i A_t + (\beta^s_i + \tilde{\beta}^s_i) B^s_t + \kappa^s_{i,b} B^b_t + \zeta^s_i C_{i,t} + \upsilon^s_i U^s_{i,t} + \kappa^s_{i,EU^s} U^s_{EU,t} + \kappa^s_{i,US^s} U^s_{US,t}$$
$$+\kappa^s_{i,EU^b} U^b_{EU,t} + \kappa^s_{i,US^b} U^b_{US,t}, \qquad \text{and,} \quad (3.13)$$

$$x^b_{i,t} = \alpha^b_i A_t + (\beta^b_i + \tilde{\beta}^b_i) B^b_t + \kappa^b_{i,s} B^s_t + \zeta^b_i C_{i,t} + \upsilon^b_i U^b_{i,t} + \kappa^b_{i,EU^s} U^s_{EU,t} + \kappa^b_{i,US^s} U^s_{US,t}$$
$$+\kappa^b_{i,EU^b} U^b_{EU,t} + \kappa^b_{i,US^b} U^b_{US,t}, \qquad \text{for } i = AU, JP \text{ and } UK. \quad (3.14)$$

Additionally, Equations (3.5) and (3.7) for the US equity and bond markets now take the form:

$$x^s_{US,t} = \alpha^s_{US} A_t + (\beta^s_{US} + \tilde{\beta}^s_{US}) B^s_t + \kappa^s_{US,b} B^b_t + \zeta^s_{US} C_{US,t} + (\upsilon^s_{US} + \tilde{\upsilon}^s_{US}) U^s_{US,t}$$
$$+\kappa^s_{US,EU^s} U^s_{EU,t} + \kappa^s_{US,EU^b} U^s_{EU,t} + \kappa^s_{US,US^b} U^b_{US,t} \qquad \text{and,} \quad (3.15)$$

$$x^b_{US,t} = \alpha^b_{US} A_t + (\beta^b_{US} + \tilde{\beta}^b_{US}) B^b_t + \kappa^b_{US,s} B^s_t + \zeta^b_{US} C_{US,t} + (\upsilon^b_{US} + \tilde{\upsilon}^b_{US}) U^b_{US,t}$$
$$+\kappa^b_{US,EU^s} U^s_{EU,t} + \kappa^b_{US,US^s} U^s_{US,t} + \kappa^b_{US,EU^b} U^b_{EU,t}. \quad (3.16)$$

3.5 GMM Estimation Method

Generalized method of moments (GMM) is used to estimate the non-crisis model and the models of contagion as specified in Section 3.4. GMM provides a unified framework for inference in econometrics, and is a computationally efficient method of obtaining consistent and asymptotically normally distributed estimators of the parameters. GMM estimation does not require any extra information aside from that contained in the moment conditions. The estimation involves computing the unknown parameters by equating the theoretical moments of the model to the empirical moments of the data in both the non-crisis model and the crisis model. As the crisis period is split to specify three crisis models corresponding to the three phases of the crisis, practically it is difficult to estimate the full model containing the non-crisis model and the three crisis models together. Thus, following the strategy applied by Dungey et al. (2011), the non-crisis model is jointly estimated with one phase of the crisis at a time.

The objective functions of the GMM estimators $V_{(\cdot)}(\theta)$ accounting for the both non-crisis and the three crisis phases can be specified as:

$$\begin{aligned} V_I(\theta) &= G_0'(\theta)W_0(\theta)^{-1}G_0(\theta) + G_I'(\theta)W_I(\theta)^{-1}G_I(\theta), \\ V_{II}(\theta) &= G_0'(\theta)W_0(\theta)^{-1}G_0(\theta) + G_{II}'(\theta)W_{II}(\theta)^{-1}G_{II}(\theta), \\ V_{III}(\theta) &= G_0'(\theta)W_0(\theta)^{-1}G_0(\theta) + G_{III}'(\theta)W_{III}(\theta)^{-1}G_{III}(\theta), \end{aligned} \tag{3.17}$$

where θ is the parameter vector. The weighting matrices, $W_{(\cdot)}(\theta)$, are corrected for possible heteroskedasticity in the moment conditions (Hamilton, 1994; Newey and West, 1987). $G_{(\cdot)}(\theta)$ are the vectors containing the differences between the empirical moments and the theoretical moments of the non-crisis model and the model for crisis phase h where $h = I, II, III$, given by:

$$\begin{aligned} G_0(\theta) &= vech\left(\Psi_0(\theta)\right) - vech\left(\Phi_0(\theta)\Phi_0'(\theta)\right), \\ G_h(\theta) &= vech\left(\Psi_h(\theta)\right) - vech\left(\Phi_h(\theta)\Phi_h'(\theta)\right). \end{aligned} \tag{3.18}$$

In Equation (3.18), $\Psi_{(\cdot)}(\theta)$ refers to the empirical variance-covariance matrices and $\Phi_{(\cdot)}(\theta)\Phi_{(\cdot)}'(\theta)$ refers to the theoretical variance-covariance matrices for the non-crisis and crisis models. The empirical variance-covariance matrices for the non-crisis period and for crisis phase h are given by:

$$\begin{aligned} \Psi_0(\theta) &= \frac{1}{N_0}\sum_{t \epsilon N_0} \varepsilon_t(\theta)\varepsilon_t(\theta)', \\ \Psi_h(\theta) &= \frac{1}{N_h}\sum_{t \epsilon N_h} \varepsilon_t(\theta)\varepsilon_t(\theta)', \end{aligned} \tag{3.19}$$

respectively, where $\varepsilon_t(\theta)$ is the 10-element vector of shocks, obtained from the VAR analysis, and $N_{(\cdot)}$ represents the sample size of each period/phase. The factors are independent with zero means and unit variances, thus the theoretical variance-covariance matrices can be specified as:

$$
\begin{aligned}
E[\varepsilon_t(\theta)\varepsilon_t'(\theta)]_{t\epsilon N_0} &= \Phi_0(\theta)\Phi_0'(\theta), \\
E[\varepsilon_t(\theta)\varepsilon_t'(\theta)]_{t\epsilon N_h} &= \Phi_h(\theta)\Phi_h'(\theta).
\end{aligned} \tag{3.20}
$$

Each model contains the non-crisis model and a crisis phase h model consisting of 100 unknown parameters to estimate, while 110 empirical moments are available for each model. Of these empirical moments, $(10 \times 11)/2 = 55$ moments come from the non-crisis data set and the remaining 55 come from the crisis period data set. The GMM estimators are obtained by equating the empirical and theoretical moments. The MAXLIK library in GAUSS version 11 is applied with the BFGS algorithm for minimizing the objective function in Equation (3.17), where the gradients are computed numerically. The GMM estimators are obtained by iterating both the parameters and weighting matrices until the convergence of the empirical and theoretical moments.

If the number of theoretical moment conditions is equal to the number of empirical moment conditions, then the first order conditions force $G_{(\cdot)}(\theta) = \mathbf{0}$, thus the objective function $V_h(\theta) = 0$. However, if the number of theoretical moment conditions are greater than the number of empirical moment conditions, then $G_{(\cdot)}(\theta) \neq \mathbf{0}$, and the model is said to be over-identified. This leads to an over-identifying restrictions test which assess the adequacy of the model. Over-identifying restrictions are tested by using Hansen's J-static given by:

$$
J_h(\theta) = NV_h(\theta), \tag{3.21}
$$

where N is the total number of observations in the full model given by $N = N_0 + N_h$. $J_h(\theta)$ converges to the χ^2_{k-l} distribution asymptotically, where k is the number of moment conditions and l is the number of parameters. A rejection of these restrictions suggests that the variables included in the model satisfy the orthogonality condition.

Quantifying the relative strengths of contagion The independence assumption of the factors allows for the decomposition of the unconditional variances into the contribution of the common, market, country, idiosyncratic and contagion factors. Additionally, the relative strengths of contagion channels during each phase of the crisis are identified through its contribution to total volatility. From the theoretical variance-covariance matrix corresponding to Equation (3.10), total volatility during the crisis can be expressed as:

$$Var(y_t) = \alpha_A^2 + \Lambda_B^2 + \zeta_C^2 + \Upsilon_U^2. \tag{3.22}$$

The contribution of each factor including the relative strength of contagion during each crisis phase can be calculated from the parameter estimates of the model. For example, consider excess returns on bonds in Australia during phase I of the crisis. The total volatility of excess bond returns in Australia can be expressed as:

$$\begin{aligned} Var(y^b_{AU,t}) = {} & (\alpha^b_{AU})^2 + (\kappa^b_{AU,s})^2 + (\beta^b_{AU} + \tilde{\beta}^b_{AU})^2 + (\zeta^b_{AU})^2 + (\kappa^b_{AU,UK^s})^2 \\ & + (\kappa^b_{AU,US^s})^2 + (\upsilon^b_{AU})^2 + (\kappa^b_{AU,UK^b})^2 + (\kappa^b_{AU,US^b})^2. \end{aligned}$$

Thus, the percentage contribution of equity market contagion to the total volatility in excess returns on bonds in Australia is:

$$\frac{(\kappa^b_{AU,s})^2 \times 100}{Var(y^b_{AU,t})},$$

and the percentage contribution of the idiosyncratic US equity market contagion on the Australian bond returns is:

$$\frac{(\kappa^b_{AU,US^s})^2 \times 100}{Var(y^b_{AU,t})}.$$

The total percentage contribution of contagion from all sources of contagion on the Australian bond returns is:

$$\frac{[(\kappa^b_{AU,s})^2 + (\kappa^b_{AU,UK^s})^2 + (\kappa^b_{AU,US^s})^2 + (\kappa^b_{AU,UK^b})^2 + (\kappa^b_{AU,US^b})^2] \times 100}{Var(y^b_{AU,t})}.$$

Likewise, the percentage contributions of financial contagion can be quantified and investigated for each market in each country for each phase of the crisis.

3.6 Empirical Results

This Section reports the results of the empirical latent factor model of contagion specified in Section 3.4. Tables 3.2 and 3.3 present the volatility decompositions of the components of contagion and aggregate contagion to total volatility in equity and bond markets for the three phases of the crisis, respectively. For comparison, the results of the factor model for the non-crisis period, estimated concurrently with each crisis phase, is presented in Appendix A.2 and the percentage contribution of the non-contagion factors to total volatility during the crisis period is presented in Appendix A.3.

Sections 3.6.1-3.6.3 discuss these key results in detail. Statistical significance of the contagion channels and structural breaks is discussed in Sections 3.6.4 and 3.6.5, respectively. Section 3.6.6 reports the results of two diagnostic tests, and Section 3.6.7 performs a sensitivity analysis of the results to alternative European sources.

3.6.1 The existence of contagion

This Section establishes the existence of contagion by focusing on the total contagion results reported in Tables 3.2 and 3.3. The results show that the effects of contagion during the three phases of the crisis of 2007-2011 are widespread across international financial markets in all five countries. The only exception is the contribution of contagion across bond markets during phase I of the crisis, which are found to be relatively low.

As shown in Table 3.2, the UK and the European equity markets are the most affected during the first two phases of the crisis, indicating that the effects of the first two phases mainly spread across the UK and Europe. Australian equity markets are also found to be highly affected from contagion effects during the first two phases. The least affected during these two phases is the Japanese equity market (28.51 percent and 32.06 percent, respectively). However, the Japanese equity market is found to be the hardest hit in the third phase of the crisis (57.71 percent). The relative strengths of contagion transmission to the European and the UK equity markets weaken significantly during the third phase compared to the first two phases. The US equity market is found to be the least affected during the third phase of the crisis (11.90 percent). This indicates that the US

Table 3.2: Contribution of Contagion Channels to Equity Market Volatility During Three Phases of the Crisis. Percentage of Total Volatility.

		Phase I	Phase II	Phase III
AU	Global bond market	6.01	3.05	1.39
	Idiosyncratic			
	UK/EU equity market	0.09	7.85	2.65
	US equity market	3.35	2.74	35.66
	UK/EU bond market	9.36	1.30	5.87
	US bond market	56.91	55.70	1.62
	Total contagion	75.72	70.64	47.19
EU	Global bond market	2.06	0.73	1.03
	Idiosyncratic			
	UK/EU equity market	0.51	0.52	n.a.
	US equity market	21.34	19.11	18.12
	UK/EU bond market	0.15	0.03	9.29
	US bond market	57.08	71.53	0.02
	Total contagion	81.14	91.92	28.46
JP	Global bond market	3.15	3.28	1.57
	Idiosyncratic			
	UK/EU equity market	3.46	2.41	3.00
	US equity market	7.46	9.29	48.96
	UK/EU bond market	0.12	0.13	2.22
	US bond market	14.32	16.95	1.96
	Total contagion	28.51	32.06	57.71
UK	Global bond market	2.88	0.04	1.71
	Idiosyncratic			
	UK/EU equity market	n.a.	n.a.	0.84
	US equity market	32.99	10.36	29.32
	UK/EU bond market	0.24	5.23	3.46
	US bond market	59.48	63.31	0.61
	Total contagion	95.59	78.94	35.94
US	Global bond market	0.12	0.22	0.99
	Idiosyncratic			
	UK/EU equity market	24.77	0.63	0.87
	US equity market	n.a.	n.a.	n.a.
	UK/EU bond market	2.83	0.49	5.56
	US bond market	24.80	43.55	4.48
	Total contagion	52.52	44.89	11.90

Note: UK asset markets are replaced by EU asset markets in specifying idiosyncratic contagion channels in crisis phase III. Crisis phase I covers the period from July 17, 2007 to September 12, 2008, phase II covers the period from September 15, 2008 to June 30, 2009, and phase III covers the period from July 01, 2009 to December 30, 2011. n.a. denotes not applicable.

Table 3.3: Contribution of Contagion Channels to Bond Market Volatility During Three Phases of the Crisis. Percentage of Total Volatility.

		Phase I	Phase II	Phase III
AU	Global equity market	0.17	12.70	17.01
	Idiosyncratic			
	UK/EU equity market	0.10	3.62	21.21
	US equity market	0.24	3.56	0.55
	UK/EU bond market	2.16	0.12	10.66
	US bond market	6.96	18.48	2.32
	Total contagion	9.63	38.48	51.75
EU	Global equity market	12.49	29.00	4.72
	Idiosyncratic			
	UK/EU equity market	0.00	2.39	1.34
	US equity market	0.09	7.59	1.31
	UK/EU bond market	21.72	2.62	n.a.
	US bond market	0.39	17.85	20.50
	Total contagion	34.69	59.45	27.87
JP	Global equity market	0.59	22.39	39.35
	Idiosyncratic			
	UK/EU equity market	0.05	1.29	2.17
	US equity market	0.09	9.46	1.29
	UK/EU bond market	1.44	0.10	11.74
	US bond market	20.46	33.49	10.40
	Total contagion	23.43	66.73	64.95
UK	Global equity market	16.57	13.63	0.01
	Idiosyncratic			
	UK/EU equity market	0.25	9.68	0.17
	US equity market	0.10	1.30	13.65
	UK/EU bond market	n.a.	n.a.	41.16
	US bond market	0.56	6.96	10.14
	Total contagion	17.48	31.57	65.13
US	Global equity market	3.03	35.46	45.59
	Idiosyncratic			
	UK/EU equity market	0.20	12.63	3.34
	US equity market	0.58	1.94	10.50
	UK/EU bond market	2.52	0.50	1.49
	US bond market	n.a.	n.a.	n.a.
	Total contagion	6.33	50.53	60.92

Note: UK asset markets are replaced by EU asset markets in specifying idiosyncratic contagion channels in crisis phase III. Crisis phase I covers the period from July 17, 2007 to September 12, 2008, phase II covers the period from September 15, 2008 to June 30, 2009, and phase III covers the period from July 01, 2009 to December 30, 2011. n.a. denotes not applicable.

equity market tends to stabilize during the third phase of the crisis. Overall, the total contagion results reported in Table 3.2 suggest that the transmission of contagion across international equity markets has become significantly weaker in phase III for all countries, except Japan.

Total contagion results reported in Table 3.3 show that the relative contribution of contagion across bond markets during the first phase of the crisis is relatively low compared to the other two phases. The least affected bond market during phase I is the US (6.33 percent) being primarily a transmitter of contagion during this phase. The hardest hit during phase I is the European bond market (34.69 percent), implying that the European bond market is more vulnerable to the shocks originating in the US financial markets than any other country considered in this Chapter during the first phase of the crisis.

In contrast to the results of phase I, the contribution of contagion to the volatility in all five bond markets is considerably large in phases I and II of the crisis. The European bond market is found to be the least affected during the third phase (27.87 percent), when Europe is the source country. Except for the US idiosyncratic bond market channel (20.50 percent), no other channel significantly transmits contagion to the European bond market during this phase. This confirms that the European bond market is a source during the third phase of the crisis.

3.6.2 Cross-market contagion

This Section examines the relative contributions of cross-market contagion in explaining asset market volatility during the three phases of the crisis. The global bond market effects as reported in Table 3.2 explain the transmission of contagion through the global bond market channel across five equity markets. Similarly, global equity market effects as reported in Table 3.3 explain the transmission of contagion via the global equity market channel to the five bond markets. A comparison of Tables 3.2 and 3.3 shows that bond markets are prone to contagion effects coming through shocks arising in global equity markets, but equity markets are found to be less affected by the shocks originating in the global bond markets.

The results reported in Table 3.3 show that the UK and the European bond markets are heavily affected by the global equity market channel during the first phase of the crisis (16.57 percent and 12.49 percent, respectively). These results imply that sudden shocks to the global equity market contribute to increased bond market volatility in the UK and Europe, triggering financial crises in those two countries. Although Dungey et al. (2011) suggested that the US bond market is heavily affected through the global equity market channel during the US sub-prime crisis, this Chapter finds only a limited effect.

All five bond markets are found to be vulnerable to contagion transmission through the global equity market channel during the second phase of the crisis. During this phase, the US bond market is the most affected (35.46 percent), followed by Europe (29.00 percent). The least affected is the Australian bond market (12.70 percent). Although the relative contribution decreases from phase I to phase II, the global equity market channel is still the main channel of transmitting shocks to the UK bond market.

Notably, the UK and the European bond markets are the least affected by the global equity market channel during the third phase of the crisis (0.01 percent and 4.72 percent, respectively). These two bond markets are the highest affected during the first phase. The relative importance of this global equity market channel has become negligible in the case of the UK. In contrast, the percentage contribution of the global equity market channel increases in Australia, Japan and the US. Overall, these results suggest that the role played by the global equity market channel in transmitting the effects of a financial shock varies depending on the phase and the source of the crisis.

As can be observed from Table 3.2, the Australian and Japanese equity markets are more vulnerable than other countries to the shocks arising in bond markets globally. However, these two countries did not suffer from the 2007-2011 crisis as badly as the other three countries considered in this Chapter. The least vulnerable is the US equity market. Although the 2007-2011 crisis is a phenomenon attributed to bond markets, the global bond market channel plays only a limited role in the contagion transmission mechanism across equity markets.

3.6.3 Idiosyncratic channels of contagion

This Section focuses on identifying the idiosyncratic channels through which the effects of the three phases of the crisis are transmitted across the equity and bond markets examined in this Chapter. The empirical model of contagion specified in Section 3.4 assumes that contagion is transmitted from the idiosyncratic US and UK asset market channels during the first two phases of the crisis, and from the idiosyncratic US and European asset market channels in the third phase. Tables 3.2 and 3.3 give the percentage contributions of these idiosyncratic channels of contagion to total volatility in equity and bond markets for the three phases of the crisis, respectively.

Contagion to equity markets Table 3.2 presents the relative importance of the idiosyncratic channels of contagion across equity markets. The most striking observation here is the contribution of the idiosyncratic contagion links from the US asset markets. The idiosyncratic link from the US bond market plays a dominant role in phases I and II, while the idiosyncratic US equity market channel is dominant in the contagion transmission mechanism during phase III of the crisis.

Generally, US bonds are considered as risk free safe haven assets. However, the crisis of 2007-2011 initially began in the US bond market, and the effects of the crisis spread across national borders, heavily affecting equity markets. The results clearly show this phenomenon during the first two phases of the crisis. The role of US idiosyncratic contagion channels is further evident from the relative contribution of additional links from the US equity market to equity market volatility in the UK and Europe. Note that, apart from the US, these two countries are the most affected during the initial stages of the crisis. Overall, these results suggest that the equity market crash during the crisis is mainly due to the contagion transmitted through the shocks specific to the US asset markets.

Except for the case of contagion to the US equity market during phase I of the crisis, the contribution of the additional links from the idiosyncratic UK (or Europe in phase III) equity and bond markets are found to be relatively low during the total crisis period. In all cases, the relative contribution to total equity market volatility is less than 10 percent. While shocks specific to the US financial markets have stronger effects on equity markets, shocks specific to the UK/European financial markets have only a limited effect on the equity markets in other countries. Examining 24.80 percent and 43.55 percent of the US equity market volatility during first two phases of the crisis, this Chapter provides evidence for cross-market contagion within the US.

Contagion to bond markets The results reported in Table 3.3 show the relative contributions of the idiosyncratic channels of contagion across the five bond markets considered in this Chapter. Clearly, no single channel dominates; that is, all the idiosyncratic contagion channels are at play, depending on the phase and the source of the crisis.

During the first phase of the crisis, two idiosyncratic contagion channels are in play in two bond markets—the idiosyncratic UK bond market channel in Europe and the idiosyncratic US bond market channel in Japan. Idiosyncratic links from the US or the UK financial markets are not strong in the other three bond markets, although the main contagion effect to the Australian bond market is coming through the idiosyncratic US bond market channel. However, the Japanese, Australian and European bond markets are found to be susceptible to the idiosyncratic US bond market channel in the second phase of the crisis, albeit to different degrees. Overall, it can be concluded that the shocks specific to the US bond market still play a significant role in the contagion transmission mechanisms in the first two phases of the crisis. However, the relative contributions are significantly low compared to the contributions to the equity market volatility. The only other idiosyncratic channel that plays a significant role in transmitting contagion across bond markets is the idiosyncratic UK equity market channel in the case of the US bond market during the second phase of the crisis.

The relative importance of the idiosyncratic contagion channels in the third phase of the crisis is complex. The highest effect comes from the idiosyncratic European bond market channel to the UK bond market. Additionally, shocks attributed to the US equity and bond markets are also important in the contagion transmission to the UK bond market. In the case of the Australian bond market, both the idiosyncratic European equity and bond market channels are at play, while the additional links from the US bond market is at play in the European bond market. The idiosyncratic shocks attributed to the bond markets of the US and Europe are important for the contagion transmission to the Japanese bond market. Shocks specific to the US equity market are at play in the US bond market, which provides evidence for cross-market contagion in phase III. However, a careful investigation reveals the spread of contagion through the same class of asset market, in the case of international bond markets.

3.6.4 Statistical significance of contagion

The results show that the percentage contributions of channels of financial contagion vary across a wide range, as some channels are highly contagious, while the others are not. Therefore, it is desirable to test the statistical significance of these transmission mechanisms. Diagnostic tests based on the Wald test are conducted to test the null hypothesis of no contagion for each phase of the crisis against the alternative hypotheses of the transmission of contagion jointly through the channels of: i) equity markets; ii) bond markets; iii) idiosyncratic European, UK and US equity markets; and iv) idiosyncratic European, UK and US bond markets. Finally, it tests the joint significance of all contagion channels for each phase of the crisis. The results are reported in Table 3.4.

The test statistics find strong evidence to reject the null hypotheses of no contagion at the 1 percent significance level in all three phases of the crisis for all the channels tested. Although the effects coming through certain channels seem to be too small to explain the volatilities in certain asset markets, they cannot be disregarded in the modeling framework, as they are statistically significant. Therefore, all the contagion channels have significant effect in transmitting financial market shocks during all three phases of the crisis.

3.6.5 Statistical significance of structural breaks

This Section tests for the statistical significance of the structural breaks introduced to the model of contagion. The model is specified allowing for the market and idiosyncratic factors to exhibit structural breaks between the non-crisis and crisis periods. Again, the Wald tests are applied to test the null hypothesis of no structural breaks against the alternative hypotheses of joint structural breaks in equity and bond markets, separately. It also tests the statistical significance of structural breaks in idiosyncratic Europe, UK and US equity and bond markets. The joint significance of all of the structural breaks is also tested, and the results are reported in Table 3.5. If the test statistics find evidence to reject the null hypothesis of no structural breaks, this suggests that the effects of these parameters are same as in the non-crisis period, and are not affected by sudden changes in the factor structure in the crisis period.

The test statistics reveal that all the structural breaks, except for the id-

Table 3.4: Statistical Significance of Contagion Channels.

Channel	DOF	Phase I	Phase II	Phase III
Equity market	5	18.57 (0.002)	195.68 (0.000)	45.80 (0.000)
$\kappa^{b}_{i,s} = 0$				
Bond market	5	19.43 (0.002)	565.76 (0.000)	116.49 (0.000)
$\kappa^{s}_{i,b} = 0$				
Idio. EU equity	9	n.a.	n.a.	87.23 (0.000)
$\kappa^{j}_{i,EU^s} = 0$				
Idio. UK equity	9	119.48 (0.000)	1406.26 (0.000)	n.a.
$\kappa^{j}_{i,UK^s} = 0$				
Idio. US equity	9	230.04 (0.000)	4335.59 (0.000)	1217.52 (0.000)
$\kappa^{j}_{i,US^s} = 0$				
Idio. EU bond	9	n.a.	n.a.	2007.74 (0.000)
$\kappa^{j}_{i,EU^b} = 0$				
Idio. UK bond	9	98.66 (0.000)	368.86 (0.000)	n.a.
$\kappa^{j}_{i,UK^b} = 0$				
Idio. US bond	9	294.94 (0.000)	15751.08 (0.000)	632.82 (0.000)
$\kappa^{j}_{i,US^b} = 0$				
Joint contagion	46	892.47 (0.000)	4718.05 (0.000)	3198.37 (0.000)

Note: Test statistics are based on the Wald test for all $j = s, b$ and $i = AU, EU, JP, UK$ and US. In each case related to the idiosyncratic channels, there are 9 degrees of freedom (DOF), as the crisis model assumes that there is no contagion effect to the own market. Joint contagion is tested by setting all the contagion channels equal to zero. p-values are in parentheses. n.a. denotes not applicable.

iosyncratic US equity market structural break in phase I and the idiosyncratic US bond market structural break in phase III, are significant at the 5 percent level. Further, the test statistics suggest that the structural breaks are jointly significant in the model.

3.6.6 Diagnostic tests

This Section reports the results of two diagnostic tests. Two conditional moment tests are used to check for first order autocorrelation (AR) and heteroskedasticity (ARCH) in the standardized residuals and standardized squared residuals of the VAR, respectively. The main advantage of these two tests is the quick implementation through an auxiliary regression. One lag is considered in the conditional moment tests in order to be consistent with the VAR model that used to filter data for the empirical exercise. Table 3.6 reports the p-values of the test statistics of AR(1) and ARCH(1) tests, which test no autocorrelation and

Table 3.5: Statistical Significance of Structural Breaks.

Structural Break	DOF	Phase I	Phase II	Phase III
Equity market $\tilde{\beta}_i^s = 0$	5	731.29 (0.000)	396.00 (0.000)	347.18 (0.000)
Bond market $\tilde{\beta}_i^b = 0$	5	19.02 (0.002)	92.92 (0.000)	23.10 (0.000)
Idio. EU equity $\tilde{\upsilon}_{EU}^s = 0$	1	n.a.	n.a.	15.69 (0.000)
Idio. UK equity $\tilde{\upsilon}_{UK}^s = 0$	1	11.66 (0.000)	10.07 (0.000)	n.a.
Idio. US equity $\tilde{\upsilon}_{US}^s = 0$	1	1.30 (0.255)	40.81 (0.000)	51.64 (0.000)
Idio. EU bond $\tilde{\upsilon}_{EU}^b = 0$	1	n.a	n.a.	5.16 (0.000)
Idio. UK bond $\tilde{\upsilon}_{UK}^b = 0$	1	23.55 (0.000)	4.65 (0.000)	n.a.
Idio. US bond $\tilde{\upsilon}_{US}^b = 0$	1	58.54 (0.000)	45.96 (0.000)	0.28 (0.599)
Joint test	14	1041.29 (0.000)	1102.93 (0.000)	824.82 (0.000)

Note: Test statistics are based on the Wald test for all $i = AU, EU, JP, UK$ and US. The joint significance is tested by setting all the structural break terms equal to zero. p-values are in parentheses. n.a. denotes not applicable.

no heteroskedasticity under null hypotheses for each phase of the crisis. Except for a few cases, the conditional moment tests fail to reject the null hypotheses at the 1 percent level, suggesting that the standardized residuals do not suffer from autocorrelation or heteroskedasticity problems.

3.6.7 Sensitivity to alternative European crisis sources

This Section checks the sensitivity of the results of phase III of the crisis to alternative European sources. Germany is used in the empirical contagion analysis to represent the European region, and used as a source of the crisis in the phase III model. But, Germany was not affected by the European debt crisis until the end of 2011, rather playing a role in bailing out some crisis affected countries, such as Greece. The contagion model of phase III is re-run, replacing Germany with Greece and Italy. The results are reported in Table 3.7.

The models which use Greece and Italy as alternative sources also find strong evidence for the spread of contagion across international equity and bond markets, which align with the phase III empirical results presented in Tables 3.2 and 3.3.

Table 3.6: Conditional Moment Tests of the Standardized VAR(1) Residuals: p-values.

Country	Test	Phase I		Phase II		Phase III	
		Equity	Bond	Equity	Bond	Equity	Bond
AU	AR(1)	0.261	0.105	0.130	0.525	0.862	0.118
	ARCH(1)	0.023	0.997	0.082	0.496	0.637	0.070
EU	AR(1)	0.604	0.943	0.062	0.490	0.000	0.159
	ARCH(1)	0.002	0.852	0.042	0.070	0.335	0.007
JP	AR(1)	0.569	0.196	0.261	0.599	0.753	0.053
	ARCH(1)	0.119	0.661	0.611	0.095	0.544	0.323
UK	AR(1)	0.524	0.117	0.048	0.820	0.279	0.000
	ARCH(1)	0.034	0.061	0.070	0.037	0.617	0.095
US	AR(1)	0.822	0.516	0.003	0.185	0.003	0.063
	ARCH(1)	0.498	0.599	0.077	0.937	0.625	0.845

All the channels are at play in transmitting contagion effects to international asset markets, and are statistically significant (see Appendix A.4), again consistent with the previously reported results for Germany. However, the results show that the relative contributions of total contagion, as well as the relative importance of each contagion channel, differ depending on Germany, Italy or Greece is used as the source crisis country.

3.7 Conclusion

The objective of this Chapter was to investigate the evidence for contagion on and among equity and bond markets, and to examine variations in the contagion transmission mechanisms during different phases of the crisis of 2007-2011. The crisis of 2007-2011 provides a natural testing ground for identifying contagion transmission mechanisms in several phases: the US sub-prime crisis (phase I), the global financial crisis (phase II), and the European debt crisis (phase III).

The model was developed based on a latent factor model of excess asset returns. In the model, each asset return was specified as a linear combination of common, market, country, idiosyncratic and contagion components. Contagion transmission mechanisms were identified through additional links from global and idiosyncratic asset markets, which appear only during the crisis. The assumption of independent, zero mean and unit variance of factors enable a convenient method for decomposing the volatility of excess asset returns into the underlying factors, including contagion. Another important feature of the model specifica-

Table 3.7: Evidence of Equity Market and Bond Market Contagion During Crisis Phase III with Alternative European Crisis Sources: Greece and Italy. Percentage of Total Volatility.

		Equity market contagion		Bond market contagion	
		with Greece	with Italy	with Greece	with Italy
AU	Global equity market	n.a.	n.a.	3.37	13.66
	Global bond market	12.72	0.07	n.a.	n.a.
	Idiosyncratic				
	EU equity market	8.69	12.09	5.15	7.34
	US equity market	12.23	2.52	6.15	0.02
	EU bond market	0.49	4.27	12.66	10.63
	US bond market	37.43	2.52	49.22	8.05
	Total contagion	71.56	21.47	76.55	39.70
EU	Global equity market	n.a.	n.a.	0.58	41.64
	Global bond market	7.25	9.75	n.a.	n.a.
	Idiosyncratic				
	EU equity market	n.a.	n.a.	16.45	0.15
	US equity market	2.38	2.54	0.10	11.93
	EU bond market	1.49	3.47	n.a.	n.a.
	US bond market	61.96	35.52	14.75	1.88
	Total contagion	73.08	51.28	31.88	55.60
JP	Global equity market	n.a.	n.a.	11.45	37.06
	Global bond market	13.24	0.05	n.a.	n.a.
	Idiosyncratic				
	EU equity market	17.42	16.66	3.48	4.92
	US equity market	4.74	2.54	0.08	0.01
	EU bond market	1.07	4.49	7.76	4.79
	US bond market	24.68	0.11	43.95	17.03
	Total contagion	61.15	23.85	66.72	63.81
UK	Global equity market	n.a.	n.a.	0.76	1.91
	Global bond market	3.06	5.18	n.a.	n.a.
	Idiosyncratic				
	EU equity market	4.83	15.31	19.51	0.02
	US equity market	10.57	9.89	11.57	35.59
	EU bond market	0.06	1.68	18.88	12.51
	US bond market	60.53	5.33	1.18	24.42
	Total contagion	79.05	37.39	51.90	74.45
US	Global equity market	n.a.	n.a.	13.33	51.80
	Global bond market	3.80	9.70	n.a.	n.a.
	Idiosyncratic				
	EU equity market	18.94	9.43	0.13	14.75
	US equity market	n.a.	n.a.	0.01	0.01
	EU bond market	0.40	2.82	5.73	0.97
	US bond market	45.66	0.63	n.a.	n.a.
	Total contagion	68.80	22.58	19.20	67.53

Note: Contribution on non-contagion components can be obtained from subtracting total contagion from 100. n.a. denotes not applicable.

tion is that change of the idiosyncratic channels in different phases of the crisis, better capturing the effects of contagion from source asset markets in different phases.

The results indicate that contagion was highly prevalent in both classes of asset markets in all three phases of the crisis. All five countries were affected by contagion, which suggest that developed country asset markets were vulnerable to the shocks attributed to the three phases of the crisis. These results agree with Longstaff (2010) and Metiu (2012), who found strong evidence for contagion during the crisis. However, the results are in contrast to Bekaert et al. (2011), who found only a small effect of systematic contagion from US financial markets and from the global financial sector.

Expanding the findings of Dungey et al. (2011) who suggested that the relative strengths of contagion channels differ across crises, this Chapter establishes that the transmission mechanism of financial contagion dynamically evolved even within a crisis. The results found that the relative contribution of each channel of contagion to the total volatility of excess returns of equities and bonds varied across the three phases of the crisis of 2007-2011. That is, the contagion transmission mechanisms varied across asset markets depending on the phase (timing) and the source (location) of the crisis.

The international bond markets were found to be susceptible to the shocks originated in the global equity market, however, the reverse existed only to a lesser extent. This finding is in contrast to the existing studies which suggested that the conditional correlation between equity and bond returns declines when equity markets suffer from financial turmoil, as investors move capital from equities to government bonds—the safer assets (Boyer et al., 2006; Kim et al., 2006). This distinction may be because of the crisis of 2007-2011 originated in bond markets.

The findings of this Chapter improves the understanding of the sources, vulnerabilities and contagion transmission mechanisms, which helps designing policies to contain the global spread of a crisis. The existence of contagion in all three phases of the crisis highlight the need to design and implement better policy measures, such as development of contingency plans to manage systematic failures. Contingency plans should consider all the aspects of the crisis, including contagion effects that go beyond a country's own economy, and also the relative importance of the channels through which contagion transmits over different phases of the crisis. Therefore, the finding of dynamic changes in the contagion transmission mechanism in different phases of the crisis is the most important policy-relevant outcome of this Chapter.

Given that the crisis originated in the benchmark asset market, the use of the US benchmark bond rate to compute excess asset returns could be seen as a limitation of this Chapter. Dungey (2008) sought to capture this phenomenon considering only the US sub-prime crisis, however, incorporating both the US originated crisis, as well as the European crisis, will be a challenge. Extending the empirical analysis to include a set of emerging market economies will improve the model by enabling a distinction of the contagion effects between developed and emerging economies. A larger country set will also enable identification of the effects of more factors, such as emerging market factors and/or regional factors.

Chapter 4

Foreign Exchange Intervention and Volatility in Emerging Economies: A GARCH Approach

4.1 Introduction

The motives for central banks to intervene in the foreign exchange market include reducing the economic costs associated with exchange rate volatility which affects international trade, financial flows, foreign investment and economic growth, and accumulating international reserves to strengthen a country's macroeconomic fundamentals (Szakmary and Mathur, 1997; Sarno and Taylor, 2001; Disyatat and Galati, 2007; Pontines and Rajan, 2011). The weight placed on each of these objectives at any point in time is likely to be a function of the prevailing domestic economic environment including policy regime choices, the external economic environment, as well as the general level of development of a country.

Foreign exchange intervention—that is, buying and selling of foreign exchange against the home currency —has often been used as an important policy tool in offsetting the effects of currency fluctuations. While accepting greater flexibility in principle, many central banks, especially in emerging markets, have intervened in their foreign exchange markets frequently, and sometimes on a large scale (Guimarães and Karacadag, 2004). For emerging markets, containing excessive volatility is particularly important as they are arguably more prone to external shocks than their developed counterparts. Understanding the effects of intervention is also of importance in managing the development process, particularly for countries who are transitioning to an inflation targeting monetary policy system, such as Sri Lanka (Anand et al., 2011). Meanwhile, accumulating international reserves helps to establish the confidence of foreign investors in the domestic economy by providing a positive impact on credit ratings. Additionally, the vulnerability to external shocks can be alleviated through a high level of reserve adequacy (Mulder and Perrelli, 2001; Dominguez et al., 2011).

This Chapter aims to examine the effectiveness of foreign exchange intervention in emerging economies using Sri Lanka as an example. Although there is a large body of literature on foreign exchange intervention, the majority of studies focus on advanced economies (Dominguez and Frankel, 1993; Sarno and Taylor, 2001; Kim and Sheen, 2002). There is only a little published work on the effects of intervention in emerging markets. Even though frequent intervention by the central bank, either through purchases or sales, is a focal element of the foreign exchange market in Sri Lanka, no studies have been formally conducted to investigate the effectiveness of this policy instrument.[1] This Chapter fills the gap in the literature.

As officially stated, the intention of the central bank in intervening in the foreign exchange market is to contain excessive volatility in the exchange rate in the short-term, and to accumulate international reserves in the medium-term (Central Bank of Sri Lanka, 2007).[2] Given these objectives, for intervention to be effective, it should have no significant effect on exchange rate returns; rather it should reduce the volatility of daily returns. The full sample period under investigation extends from January 2002 to December 2010, and is divided into two sub-periods: i) "the non-crisis period;" and ii) "the crisis period." These two periods allow an examination of how the Central Bank of Sri Lanka responded to volatility arising in global financial markets compared to the non-crisis period.

The empirical investigation is based on Generalized Autoregressive conditional heteroskedasticity (GARCH) specifications. Comparing GARCH(1,1), threshold

[1]The only study relates to central bank intervention in Sri Lanka is Anand et al. (2011), in which intervention is discussed in the context of the role of exchange rates in inflation targeting.

[2]The Central Bank of Sri Lanka notes that intervention is not aimed at targeting an exchange rate level (Central Bank of Sri Lanka, 2007), indicating that the intervention strategy is to "lean against the wind" to reduce exchange rate volatility. However, the central bank does not define the meaning of "excessive volatility", hence, there is no formal rule governing when intervention should occur.

GARCH(1,1) and exponential GARCH(1,1), this Chapter finds that the exponential GARCH (EGARCH) as the best model that fits the data in evaluating the effects of foreign exchange intervention in Sri Lanka. The empirical results found are supportive for the effectiveness of foreign exchange intervention in Sri Lanka. This Chapter reveals that intervention reduces exchange rate volatility rather than altering the exchange rate trend. The economically insignificant effects on daily exchange rate returns, and the significant reduction in exchange rate volatility is consistent with the short- and medium-term objectives of intervention. However, the effect of intervention on the conditional volatility during the crisis period is not as strong as that of the non-crisis period. A drawback of the EGARCH model is its inability to assess numerically the effect of intervention on the conditional volatility of exchange rate returns. Therefore, a new empirical methodology is developed in the next Chapter to complement the results established in this Chapter.

The remainder of this Chapter is organized as follows. Section 4.2 reviews existing literature on foreign exchange intervention. Section 4.3 provides a description of data used in this study. The GARCH methodology is specified in Section 4.4. The empirical results of the efficacy of central bank intervention, during the non-crisis period and in the crisis period, are discussed in Section 4.5. Section 4.6 concludes.

4.2 Literature Review

The literature on foreign exchange intervention has mainly focused on the effects on exchange rate returns and its volatility. The other aspect of intervention, that is reserve accumulation, is now attracting attention particularly in the context of the role played by emerging markets in the face of the financial crisis. Important papers examining this issue include Dominguez (2010), Adler and Tovar (2011), Dominguez et al. (2011) and Pontines and Rajan (2011).

There is a large body of literature on the effects of foreign exchange intervention on exchange rate volatility. However, the majority of these studies is related to advanced economies (Dominguez, 1998; Fatum, 2003; Fatum and Hutchison, 2006; Sarno and Taylor, 2001). With the notable exception of Disyatat and Galati (2007), there is a little published work on the effects of intervention in emerging markets, although central banks, the International Monetary Fund (IMF) and the Bank for International Settlements (BIS) aim to fill this gap (Pattanaik and Sahoo, 2001; Mandeng, 2003; Guimarães and Karacadag, 2004; BIS, 2005; Herrera and Ozbay, 2005; Kamil, 2008; Adler and Tovar, 2011). Edison (1993), Sarno and Taylor (2001) and Disyatat and Galati (2007) provide good surveys of empirical methods and evidence to more generally evaluate intervention and its effects on exchange rate volatility.

Empirical evidence on the effectiveness of foreign exchange intervention in advanced economies is inconclusive. That is, some studies find strong evidence in favor of foreign exchange intervention (Hung, 1997; Dominguez, 1998; Fatum, 2003; Fatum and Hutchison, 2006), while others find that intervention is not effective (Bonser-Neal and Tanner, 1996; Hung, 1997; Dominguez, 1998; Beine et al., 2002). In contrast to the inconclusive findings of intervention in advanced economies, empirical studies on emerging economies are more supportive of intervention being effective in reducing exchange rate volatility without affecting the exchange rate trend (Disyatat and Galati, 2007). Domaç and Mendoza (2004), Shah et al. (2009) and Adler and Tovar (2011) also suggest that foreign exchange intervention in emerging markets effectively reduces exchange rate volatility even if it does not alter the current trend of exchange rate movements. In contrast, Simwaka (2011) recently found that intervention tends to increase exchange rate volatility, although it significantly changes the exchange rate trend. Abenoja (2003) supports this argument, suggesting that persistent intervention can actually increase exchange rate volatility, even though contemporaneous intervention tends to decrease within-day volatility.

In the Sri Lankan context, only one study, by Anand et al. (2011), have investigated the effectiveness of central bank intervention. In an effort to assess whether Sri Lanka is ready for inflation targeting, Anand et al. (2011) studied the role of intervention and found that the central bank attempts to alter the exchange rate trend, and curtails excess volatility since March 2005. However, Anand et al. (2011) used changes in official intervention to proxy for intervention.

A range of analytical techniques has been used to investigate the effectiveness of foreign exchange intervention including structural approaches, event-study approaches and GARCH frameworks. Structural methods estimate a system of equations using the instrumental variable approach or applying the two-stage least-square approach (Obstfeld, 1982; Gärtner, 1987; Galati et al., 2005; Disyatat and Galati, 2007). The event-study approach allows users to evaluate the effects of every single intervention "event" on exchange rate changes, with special attention given to the environment in which the events are defined (Fatum, 2003; Fatum and Hutchison, 2006; Mandeng, 2003). However, the effectiveness of foreign exchange intervention is often evaluated through various forms of GARCH specifications (Almekinders and Eijffinger, 1996; Dominguez, 1998; Beine et al., 2002; Domaç and Mendoza, 2004; Guimarães and Karacadag, 2004; Hoshikawa, 2008). The reason for the extensive use of the GARCH methodology is that it tests the effects of intervention on both the conditional mean and variance of exchange rate returns simultaneously, while capturing volatility clustering in financial time series, different to the other methodologies.

4.3 Data Description

The effectiveness of foreign exchange intervention is investigated using a unique data set obtained from the Central Bank of Sri Lanka. The data are of daily frequency and covered the period from January 01, 2002 to December 31, 2010. This period is selected due to the availability of daily foreign exchange intervention data, and in order to cover the post-float era in Sri Lanka.[3] For estimation purposes, the sample period is divided into two sub-periods: January 01, 2002 to June 29, 2007 and July 02, 2007 to December 31, 2010. The first sub-period covers a relatively low volatility period in the global foreign exchange markets compared to the latter, in which the volatility is much higher due to the recent financial crisis. In the Sri Lankan context, the latter period is not only coincides with the recent financial crisis, but also the final phase of the civil war in Sri Lanka that had prevailed for over 25 years.

The variables employed in the analysis include exchange rate returns of the Sri Lankan rupee ($dler_t$), net foreign exchange intervention (int_t), the interest rate differential (dif_t) and the government bond spread (spr_t). Intervention is modeled separating the purchases (pur_t) and the sales (sel_t) for better explanation of the effects of intervention. The exchange rate data used in this Chapter are daily

[3] Daily data on official intervention in the foreign exchange market is not publicly available, but is available for internal use of the central bank.

average interbank rates, that are expressed as Sri Lankan rupees per US dollar. Thus, an increase in the exchange rate corresponds to a depreciation of the Sri Lankan rupee. Exchange rate returns are computed by taking the first difference of the natural logarithm of the exchange rates and multiplying it by 100. Foreign exchange intervention is expressed in millions of US dollars.

The interest rate differential is the difference between the Sri Lankan 3-month Treasury bill rate and the US 3-month Treasury bill rate. In the context of foreign exchange intervention, the use of interest rate differentials in the model captures the possible effects of intervention on the money market. Daily foreign exchange interventions (purchases and sales), the daily exchange rates and the 3-month Treasury bill rates were obtained from the Central Bank of Sri Lanka. The US 3-month Treasury bill rates and US government bond rates were obtained from the US Federal Reserve Bank's website. As the lack of a daily bond rate series for Sri Lanka is a major limitation for this exercise, a series of daily 3-year bond rates is generated based on the available rates and their growth rates as a proxy for country risk. The series of daily 3-year bond rates is calculated using linear interpolation: $B_k = B_{t-n} + k(B_t - B_{t-n})/n$; $k = 1, 2, \ldots, (n-1)$ where B_k is the bond rate on the k^{th} day, on which the actual bond rate is not available; B_t is the next available bond rate; B_{t-n} is the previously known bond rate on the day $t-n$; and $n-1$ is the number of days that the actual bond rates are not available.

The Sri Lankan rupee expressed in both (log) levels and returns, and net foreign exchange purchases (intervention) data for Sri Lanka are shown in Figure 4.1. The log of the level of the Sri Lankan rupee is presented in panel (a), and the percentage returns are presented in panel (b). The intervention data are plotted against each of these series, with the scale of the exchange rate variables on the left side of the respective panels, and the scale of intervention on the right. Positive values of the intervention series represent purchases of US dollars and negative values represent sales. Table 4.1 presents descriptive statistics for the net intervention data for the total sample period, as well as for the sub-periods of non-crisis and crisis. Appendix B.1 presents summary statistics for the Sri Lankan rupee/US dollar exchange rate, the interest rate differential and the bond spread.

Figure 4.1 and Table 4.1 show that the magnitude of volatility for the intervention data is greater during the crisis period. The standard deviation of inter-

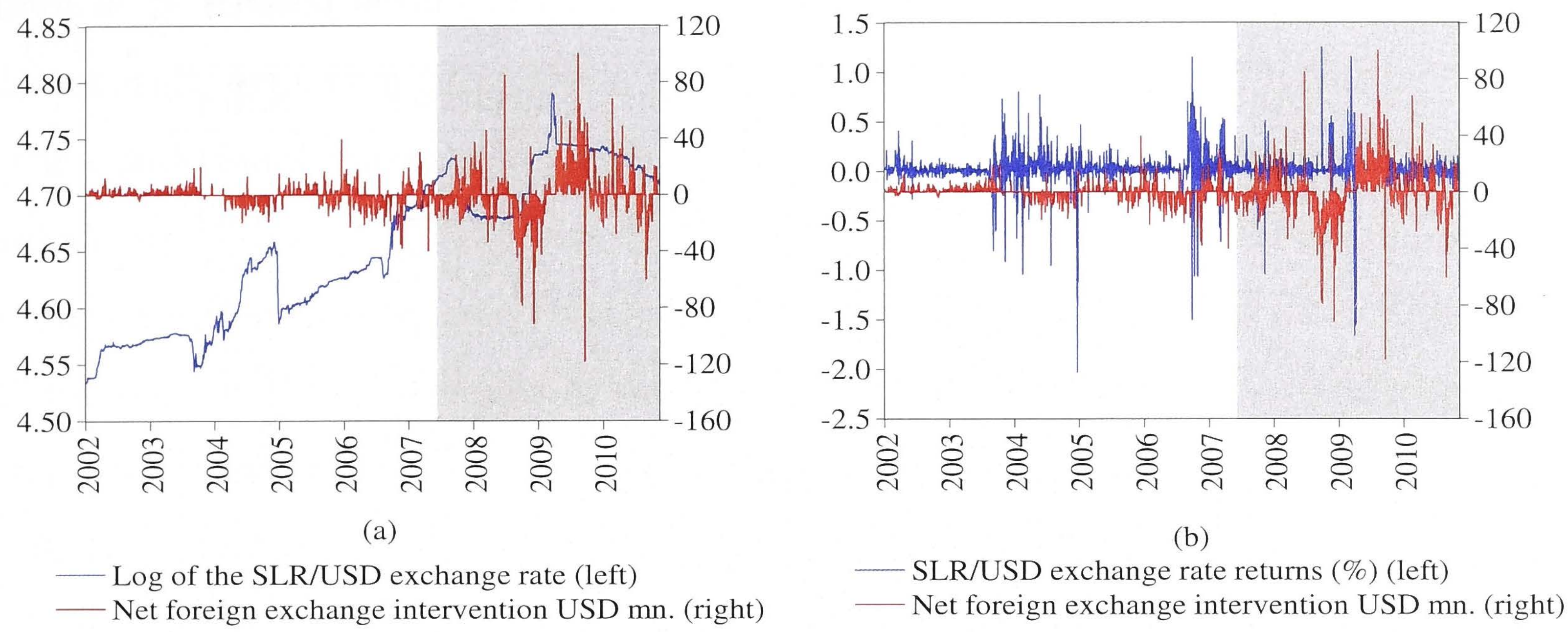


Figure 4.1: Sri Lankan Rupee Exchange Rate and Intervention Data, January 2002 to December 2010. Notes: Panel (a) is the daily log exchange rate against the US dollar and net foreign exchange intervention (US$m). Panel (b) is the percentage of daily exchange rate returns against the US dollar and net foreign exchange intervention (US$m). The shaded areas indicate the crisis period from July 2, 2007 to December 31, 2010 (Source: Central Bank of Sri Lanka).

vention increased from 7.81 million in the low volatility period to 20.03 million in the global volatility period. During this time, the Central Bank of Sri Lanka went from being a net seller to a net purchaser as shown by the statistics for the mean across two sub-periods. Meanwhile, the figure depicted in Appendix B.2 shows evidence of volatility clustering of exchange rate returns.

A Dickey-Fuller test is used to test the stationarity of the time series used in this Chapter. The null hypothesis tested is that the time series exhibits a unit root, against the alternative of stationarity. Appendix B.3 presents the results. As the interest rate differential and the bond spread are non-stationary at their level form, the first difference of these two series is used for the empirical analysis.

4.4 GARCH Models

The empirical analysis of this Chapter is based on the GARCH methodology. Various forms of the GARCH method, such as standard GARCH (Dominguez, 1998; Hillebrand and Schnabl, 2003; Behera et al., 2008), EGARCH (Hoshikawa, 2008; Goyal and Arora, 2010; Tuna, 2011), TGARCH (McKenzie, 2002; Suardi, 2008), and smooth-transition GARCH (Reitz and Taylor, 2008) have been used to model exchange rate volatility. Empirical studies tend to apply a GARCH(1,1)

Table 4.1: Descriptive Statistics for Intervention Data.

Statistics	Intervention	Purchases	Sales
Total sample			
No. of obs.	1082	547	535
Mean	0.11	9.71	-9.68
Max	99.75	99.75	-0.25
Min	-118.45	0.25	-118.45
Std. dev.	14.99	11.60	11.27
Non-crisis period			
No. of obs.	561	307	254
Mean	-0.35	4.80	-6.60
Max	39.15	39.15	-0.25
Min	-40.00	0.25	-40.00
Std. dev.	7.81	4.89	5.89
Crisis period			
No. of obs.	521	240	281
Mean	0.60	16.00	-12.47
Max	99.75	99.75	-0.25
Min	-118.45	0.50	-118.45
Std. dev.	20.03	14.36	13.91

Note: The intervention data are expressed in millions of US dollars. The statistics are calculated for each sub-period on all days there are purchases or sales of US dollars (Intervention), days on which US dollars are purchased (Purchases) and days on which US dollars are sold (Sales). The total sample is from January 1, 2002 to December 31, 2010, the non-crisis period is from January 1, 2002 to June 29, 2007, and the crisis period is from July 2, 2007 to December 31, 2010.

specification, as it provides a good fit to daily data (Baillie and Bollerslev, 1989).

Baseline GARCH(1,1) model This Chapter first applies the widely used GARCH(1,1) specification initiated by Engle and Bollerslev (1986) to examine the effect of foreign exchange intervention on the conditional mean and volatility of daily Sri Lankan rupee/US dollar exchange rate returns ($dler_t$) as follows:

$$dler_t = \beta_0 + \beta' X_t + \epsilon_t, \tag{4.1}$$

$$\epsilon_t = \sqrt{h_t} u_t, \tag{4.2}$$

$$u_t \sim i.i.d.N(0,1), \quad \epsilon_t \mid \Omega_{t-1} \sim N(0, h_t),$$

$$h_t = \omega + \alpha \epsilon_{t-1}^2 + \delta h_{t-1} + \gamma' X_t, \tag{4.3}$$

where $\omega > 0$, $\alpha \geq 0$, $\delta \geq 0$, and u_t is the standardized residual of exchange rate returns. Equation (4.1) is the conditional mean equation and Equation (4.3) is the conditional variance equation. In this framework, the returns of the Sri Lankan rupee ($dler_t$) are explained by a vector of explanatory variables X_t, which includes the purchases (pur_t) and sales (sel_t) of foreign exchange in millions of US dollars, the first difference of the interest rate differential (dif_t), and the first difference of the government bond spread (spr_t). The coefficient vector is β.

Asymmetric responses of the conditional volatility to unexpected movements in exchange rate returns are captured by the volatility equation in Equation 4.3. The unexpected return, which is represented by the error term ϵ_t, is used to model the conditional volatility of the exchange rate returns h_t. The information set available at time $t-1$ is denoted by Ω_{t-1}. Volatility clustering, or news about volatility from the previous period is captured by ϵ_{t-1}^2, the lag of the squared residuals from the mean equation. This term is also called the ARCH term. This ARCH effect usually arises from the dependency caused through the second moments of the error term. Conditional volatility is captured by h_t. The term h_{t-1} is the GARCH term, which represents the forecast of the variance of the previous period. Further, $\alpha \geq 0$ measures the extent to which a shock affects the volatility during the next period, while $\delta \geq 0$ captures the persistence of volatility. The constraints $\omega > 0$, $\alpha \geq 0$ and $\delta \geq 0$ ensure that h_t is strictly positive. The model is stationary if $(\alpha + \delta) < 1$. Finally, γ is the coefficient vector to be estimated in the variance equation.

Errors are assumed to be normally distributed. Although the distribution of exchange rate returns usually exhibit fat tails suggesting that they are not normally distributed, it has been empirically tested that using alternative distributions, such as the t-distribution or the generalized error distribution (GED), does not make a significant difference to the parameter estimation (Hentschel, 1995). For simplicity, the normal distribution assumption is used in this Chapter. If the daily exchange rate returns are modeled correctly, the parameter estimates are still consistent even if errors are not normally distributed (Bollerslev, 1986).

The interest rate differential is used to capture the relationship between the exchange rate and the interest rate. The government bond spread is included as a proxy for country risk. For intervention to influence the daily rupee returns effectively, intervention through purchases is expected to depreciate the rupee, while intervention through sales is expected to appreciate the domestic currency significantly. That is, the coefficient of purchases of US dollars β_p is expected to be positive and the coefficient of sales β_s is expected to be negative. A higher interest rate differential is expected to appreciate the exchange rate returns, and a higher spread in the government bond rates is expected to trigger declines in the Sri Lankan rupee/US dollar exchange rate.

For intervention to reduce the conditional volatility of exchange rate returns, the parameter estimates of purchases and sales of US dollars are expected to be negative and significant. A reduction in the country risk given by a reduction in the government bond spread is assumed to reduce exchange rate volatility. However, the interest rate differential can either stabilize or destabilize the exchange rate.

Augmented GARCH(1,1) model The baseline model specified above does not allow exchange rate dynamics and foreign exchange intervention to affect each other simultaneously. Further, the model does not capture possible autocorrelation in daily exchange rate returns. Therefore, the baseline model is augmented, including lagged exchange rate returns as well as lagged purchases and sales of foreign exchange. The inclusion of lagged intervention variables helps to identify the horizon at which intervention through purchases and sales affect the daily rupee returns and its volatility. The effects of exchange rate returns that may persist over several days are captured through lagged exchange rate returns. The inclusion of lagged exchange rate returns is also expected to address the autocorrelation problem. The augmented form of the baseline GARCH(1,1) model is given by:

$$dler_t = \beta_0 + \sum_{i=0}^{k} \beta_{p,i} pur_{t-i} + \sum_{i=0}^{m} \beta_{s,i} sel_{t-i} + \beta_d dif_t + \beta_{sp} spr_t + \sum_{i=1}^{n} \beta_{er,i} dler_{t-i} + \epsilon_t \tag{4.4}$$

$$h_t = \omega + \alpha\epsilon_{t-1}^2 + \delta h_{t-1} + \sum_{i=0}^{k} \gamma_{p,i} pur_{t-i} + \sum_{i=0}^{m} \gamma_{s,i} sel_{t-i} + \gamma_d dif_t + \gamma_{sp} spr_t \tag{4.5}$$

where the explanatory variables are the same as in the baseline model.

Following a general-to-specific approach, purchases and sales are included in one- and two-day lags with one day lagged exchange rate returns. Initially, five lags of intervention variables and five lags of exchange rate returns are included in the model. The lag lengths are then reduced until the last lag is found to be statistically significant, at least at the 10 percent level. The selection of lag lengths of purchases and sales of US dollars is based on a simple ordinary least squares estimate over the full sample period. Contemporaneous purchases and sales are excluded for reasons of simultaneity as the baseline GARCH estimation shows the effect of contemporaneous purchases and sales often opposite signed as it is in the case of simultaneity bias. After selecting the lag lengths, the specification takes the form:

$$dler_t = \beta_0+\sum_{i=1}^{2}\beta_{p,i}pur_{t-i}+\sum_{i=1}^{2}\beta_{s,i}sel_{t-i}+\beta_d dif_t+\beta_{sp}spr_t+\beta_{er}dler_{t-1}+\epsilon_t \quad (4.6)$$

$$h_t = \omega+\alpha\epsilon_{t-1}^2+\delta h_{t-1}+\sum_{i=1}^{2}\gamma_{p,i}pur_{t-i}+\sum_{i=1}^{2}\gamma_{s,i}sel_{t-i}+\gamma_d dif_t+\gamma_{sp}spr_t. \quad (4.7)$$

TGARCH(1,1) model The augmented GARCH(1,1) model is then compared with a threshold GARCH (TGARCH) model to test for possible asymmetries in the conditional variance equation. Equation (4.7) is modified by including a dummy variable D_{t-1}, to capture the effects of past unexpected shocks on volatility. The conditional variance equation for the TGARCH(1,1) model has the form:

$$h_t = \omega+\alpha\epsilon_{t-1}^2+\delta h_{t-1}+\tau\epsilon_{t-1}^2D_{t-1}+\sum_{i=1}^{2}\gamma_{p,i}pur_{t-i}+\sum_{i=1}^{2}\gamma_{s,i}sel_{t-i}+\gamma_d dif_t+\gamma_{sp}spr_t, \quad (4.8)$$

where $D_{t-1} = \begin{cases} 1, & \text{if } \varepsilon_{t-1} < 0; \\ 0, & \text{if } \varepsilon_{t-1} \geq 0. \end{cases}$

In this specification, the effect of an unexpected exchange rate appreciation on the conditional variance is higher than the unexpected exchange rate depreciation if $(\alpha+\tau) > \delta$ and lower otherwise, given that $\tau \neq 0$. A positive value of τ means prior negative returns have a higher effect on volatility.

EGARCH(1,1) model Recent empirical studies have shown that traditional GARCH(1,1) models underestimate the effects of intervention on the variance of exchange rate returns (Beine et al., 2002; Domaç and Mendoza, 2004). An important requirement of basic GARCH models is to impose restrictions on parameters to ensure a positive conditional variance. In an attempt to avoid the violation of the non-negativity condition, many studies include absolute values of purchases and sales of foreign exchange (or net intervention) in the variance equation, while ignoring the effect of other exogenous variables that might affect the volatility of the exchange rate returns.

Although the models expressed in Equations (4.6)-(4.8) are estimated using absolute values of the sale of US dollars, these models also include the first differences of the interest rate differential and the government bond spread. If the parameters are not restricted to be positive, there is a risk of computing a negative variance. Therefore, in estimating Equations (4.6)-(4.8), one should either restrict the parameters to be positive or ensure that the variance is always positive. The EGARCH model proposed by Nelson (1991) allows the incorporation of negative variables or parameters for the variance equation without imposing restrictions, still ensuring non-negativity in the variance. The EGARCH framework ensures that volatility is always positive, as all the terms in the conditional variance equation are derived from the exponential function. The advantage of using the EGARCH specification is that it captures asymmetric or leveraged behavior of volatility. In the context of exchange rate volatility, this refers to the characteristic of an unexpected negative shock to exchange rate returns that tends to increase exchange rate volatility disproportionately.

In the case of exchange rate volatility and intervention, the EGARCH model allows the investigation to effectively distinguish the effect of the intervention through purchases and sales, when they are expressed in positive and negative values, and a positive variance will reside regardless of whether the coefficients are positive or negative. Therefore, this study also estimates the variance of the Sri Lankan rupee returns in an EGARCH(1,1) environment, such that:

$$\ln(h_t) = \omega + \alpha|z_{t-1}| + \theta z_{t-1} + \delta \ln(h_{t-1}) + \sum_{i=1}^{2} \gamma_{p,i} pur_{t-i} + \sum_{i=1}^{2} \gamma_{s,i} sel_{t-i} + \gamma_d dif_t + \gamma_{sp} spr_t, \tag{4.9}$$

where $z_{t-1} = \epsilon_{t-1}/\sqrt{h_{t-1}}$ is the lagged standardized shock that captures asymmetric effects of positive and negative shocks. If $\theta > 0$, volatility tends to rise as the lagged standardized shock is positive ($z_{t-1} > 0$). The reverse holds if $\theta < 0$. Thus the effect of the shock is asymmetric if $\theta \neq 0$. Particularly, if $-1 < \theta < 0$, positive shocks increase volatility less than negative shocks. The persistence of volatility shocks for the EGARCH model is governed by δ. The sales are included in the empirical analysis in negative magnitudes to capture the effects of intervention when the central bank intervenes to the foreign exchange market through sales.

The GARCH(1,1), TGARCH(1,1) and EGARCH(1,1) models specified above are estimated by using maximum likelihood estimation. The most suitable model is then selected following standard model selection procedures. That is, the model that contains the lowest Akaike information criterion (AIC) and Bayesian information criterion (BIC) values, and the largest log likelihood (LogL) value, is used to select the best model that fits the data in evaluating the effectiveness of foreign exchange intervention in Sri Lanka. Additionally, the Ljung-Box statistics calculated from the first 20 autocorrelation coefficients of the standardized residuals and the standardized squared residuals ($Q(20)$ and $Q^2(20)$, respectively) are tested for remaining residual autocorrelation as it is important to have no autocorrelation in the residuals before estimating the GARCH process. The Lagrangian Multiplier (LM) test is carried out to test for ARCH effects in residuals.

4.5 Empirical Results

This Section presents empirical results on how intervention by the Central Bank of Sri Lanka in foreign exchange market effects the exchange rate returns and its volatility. To this end, this study first estimates the baseline GARCH(1,1) model explained by Equations (4.1)-(4.3) over the non-crisis period as well as over the crisis period in Section 4.5.1. Section 4.5.2 estimates the augmented GARCH(1,1) model (Equations (4.6) and (4.7)), the TGARCH(1,1) model (Equations (4.6) and (4.8)) and the EGARCH(1,1) model (Equations (4.6) and (4.9)) in order to select the best model to explain the effects of foreign exchange intervention on exchange rate returns and exchange rate volatility. The empirical results for the non-crisis period and the crisis period are discussed in Sections 4.5.3 and 4.5.4, respectively.

4.5.1 Baseline model

Table 4.2 presents estimates of the baseline GARCH(1,1) model over non-crisis and the crisis periods. Absolute volumes of purchases and sales are used in the model. The parameters are then estimated without any constraint, ensuring

Table 4.2: Baseline GARCH(1,1) Model Parameter Estimates.

Parameter	Non-crisis period	Crisis period
Conditional mean equation: coefficient(10^{-3})		
β_0	28.10 (0.012)	-10.07 (0.609)
β_p	-2.32 (0.106)	-0.18 (0.881)
β_s	-0.27 (0.824)	2.74 (0.000)
β_d	-66.79 (0.940)	23.97 (0.802)
β_{sp}	0.42 (0.312)	-0.17 (0.497)
Conditional variance equation: coefficient(10^{-3})		
ω	22.41 (0.000)	1.93 (0.000)
γ_p	-0.90 (0.000)	-0.29 (0.000)
γ_s	-0.95 (0.000)	-0.09 (0.085)
γ_d	102.94 (0.362)	7.65 (0.580)
γ_{sp}	0.41 (0.000)	-0.10 (0.003)
ARCH and GARCH terms		
α	0.298 (0.000)	0.168 (0.000)
δ	0.407 (0.000)	0.550 (0.000)
Diagnostic test statistics		
$Q(20)$	105.14 (0.000)	146.89 (0.000)
$Q^2(20)$	289.48 (0.000)	89.683 (0.000)
LM	31.461 (0.000)	22.375 (0.000)
LogL	607.687	423.968
AIC	-0.900	-0.973
BIC	-0.853	-0.906

Note: The non-crisis period is from January 01, 2002 to June 29, 2007 and the crisis period is from July 02, 2007 to December 31, 2010 (see Equations (4.1)-(4.3)). The dependent variable in the mean equation is the Sri Lankan rupee returns ($dler_t$), and the vector X_t in both the mean and the conditional variance equations includes purchases (pur_t), absolute volume of sales (sel_t), the first difference of the interest rate differential (dif_t) and the first difference of the government bond spread (spr_t). Parameter estimates are multiplied by 1000. p-values are in parentheses.

that the variance is always positive. Estimated coefficients do not exhibit a strong effect on the Sri Lankan rupee/US dollar exchange rate returns in both periods. Only the contemporaneous sale of US dollars during the crisis period (β_s) has a significant effect, but it is against prior expectations. In contrast, contemporaneous purchases (γ_p), as well as, sales (γ_s) tend to reduce exchange rate volatility significantly during both periods, even if the magnitudes of such effects are small. A change in the interest rate differential has no significant effect in reducing exchange rate volatility, whereas the effect of the change in the bond spread, though significant, is small.

The main problem associated with the baseline model is the possible correlation of the error term with the explanatory variable. Diagnostic statistics also show that the baseline model does not fit for the data under investigation. The Ljung-Box test statistics show that both the standardized residuals and the standardized squared residuals reject the null hypothesis of no autocorrelation up to order 20. The ARCH-LM tests with two lags suggest remaining ARCH effects in the residuals.[4] Therefore, the augmented GARCH(1,1), TGARCH(1,1) and EGARCH(1,1) models are tested to select the better model in examining the effectiveness of foreign exchange intervention in Sri Lanka.

4.5.2 Model selection

This Section estimates three specifications of GARCH models; the augmented GARCH(1,1), TGARCH(1,1) and EGARCH(1,1), and the results are reported in Table 4.3 for the non-crisis period. The empirical results suggest that the EGARCH(1,1) model, which allows for asymmetric effects, is the best fit to the data. The EGARCH(1,1) model is selected as the best model as it contains the largest log likelihood (LogL) value, and the lowest AIC and BIC values. The threshold term τ in the TGARCH(1,1) model is not significant, indicating that the threshold model is not needed to capture any asymmetric effects in the data.

The Ljung-Box test statistics calculated from the first 20 and 30 autocorrelation coefficients of the standardized residuals ($Q(20)$ and $Q(30)$) of the selected EGARCH(1,1) model are 31.48 (p-value $= 0.05$) and 35.69 (p-value $= 0.22$), respectively. The Ljung-Box test statistic for the standardized squared residuals ($Q^2(20)$) is 18.54 (p-value $= 0.55$). Thus, the selected EGARCH(1,1) model fails to reject the null hypothesis of no autocorrelation in residuals in longer lags at the 5 percent level. The p-value of the ARCH-LM test (0.08) suggests that there are no additional ARCH effects remaining in the residuals at the 5 percent level. Overall, the standardized diagnostic statistics show that the EGARCH(1,1) model is the best model as in comparison to the alternative models, is able to correct for heteroskedasticity in the exchange rate data, and provides less evidence of autocorrelation in the standardized residuals.

[4]The ARCH-LM test is carried out with two levels of lags based on the optimal lag length suggested for the intervention model.

Table 4.3: GARCH (1,1), TGARCH (1,1) and EGARCH (1,1) Model Parameter Estimates.

Parameter	GARCH (1,1) Eq. (4.6),(4.7)	TGARCH (1,1) Eq. (4.6),(4.8)	EGARCH (1,1) Eq. (4.6),(4.9)
Conditional mean equation: coefficient (10^{-3})			
β_0	-3.41 (0.807)	8.33 (0.657)	2.11 (0.145)
$\beta_{p,1}$	3.31 (0.119)	0.05 (0.989)	-0.99 (0.063)
$\beta_{p,2}$	1.97 (0.128)	3.54 (0.135)	2.55 (0.000)
$\beta_{s,1}$	3.33 (0.022)	-0.49 (0.791)	0.23 (0.721)
$\beta_{s,2}$	2.11 (0.131)	-1.13 (0.652)	0.08 (0.913)
β_d	-116.11 (0.893)	-152.58 (0.909)	-237.24 (0.017)
β_{sp}	0.98 (0.127)	0.49 (0.713)	-0.21 (0.001)
β_{er}	313.83 (0.000)	270.47 (0.000)	216.55 (0.000)
Conditional variance equation: coefficient(10^{-3})			
ω	25.16 (0.000)	29.00 (0.000)	-540.98 (0.000)
$\gamma_{p,1}$	-0.78 (0.000)	-0.88 (0.15)	-16.13 (0.129)
$\gamma_{p,2}$	-0.74 (0.003)	-0.89 (0.015)	-21.91 (0.020)
$\gamma_{s,1}$	-0.42 (0.036)	0.64 (0.013)	-17.48 (0.006)
$\gamma_{s,2}$	-1.08 (0.000)	-1.15 (0.000)	-4.57 (0.484)
γ_d	-148.20 (0.379)	50.25 (0.815)	5063.51 (0.012)
γ_{sp}	0.37 (0.000)	-0.022 (0.881)	5.70 (0.000)
ARCH and GARCH terms			
α	0.264 (0.000)	0.152 (0.011)	0.523 (0.000)
δ	0.454 (0.000)	0.558 (0.000)	0.964 (0.000)
τ	-	0.057 (0.400)	-
θ	-	-	-0.041 (0.001)
Diagnostic test statistics			
$Q(20)$	20.867 (0.090)	26.504 (0.150)	31.483 (0.049)
$Q^2(20)$	280.120 (0.000)	299.470 (0.000)	18.542 (0.552)
LM	35.232 (0.000)	44.1 (0.000)	2.533 (0.080)
LogL	543.066	400.583	1271.525
AIC	-0.795	-0.578	-1.895
BIC	-0.729	-0.508	-1.824

Note: Models are estimated over the non-crisis period, January 01, 2002 to June 29, 2007 (see Equations (4.6) and (4.7), (4.6) and (4.8), and (4.6) and (4.9), respectively). The dependent variable in the mean equation is the Sri Lankan rupee returns (*dler*). Absolute values of sales (sel_t) are included in the GARCH(1,1) and TGARCH(1,1) models, while total volumes of sales are used in the EGARCH(1,1) model. Parameter estimates are multiplied by 1000. p-values are in parentheses.

4.5.3 Effects of intervention during the non-crisis period

This Section analyzes the effects of foreign exchange intervention on exchange rate returns, and its volatility during the non-crisis period based on the results of the selected EGARCH(1,1) model in Table 4.3.

Effect on exchange rate returns The estimated coefficients for the intervention variables indicate that the effects of intervention on the conditional mean of the exchange rate returns are ambiguous. Interestingly, the results reveal that intervention through purchases is effective in influencing the daily exchange rate returns during the non-crisis period, but not intervention through sales. Although intervention through purchases is significant, the effect is not totally in line with prior expectations. If the purchases of US dollars are to influence the daily exchange rate returns, the coefficients $\beta_{p,1}$ and $\beta_{p,2}$ should be positive and significant. The results reveal that one-day lagged purchases $\beta_{p,1}$ tend to appreciate the Sri Lankan rupee against the prior expectations, while two-day lagged purchases $\beta_{p,2}$ tend to depreciate the exchange rate as expected.

Accordingly, a purchase of US dollars 100 million leads the rupee to depreciate by 0.16 percent in two days. In this context, the average and the maximum amounts of purchases of US dollars during the non-crisis period as presented in Table 4.1 tend to depreciate the domestic currency by 0.008 percent and 0.063 percent, respectively, within two days. Clearly, these effects are small and cannot be considered economically substantial, that is they have no significant influence on the average daily return of the Sri Lankan rupee/US dollar rate (-0.01 percent). This indicates that the central bank intervenes in the foreign exchange market through purchases mainly to build up international reserves, but not to alter the exchange rate trend. Further more, intervention through sales tends to depreciate the rupee, but both coefficients are insignificant. Economically and statistically insignificant coefficient estimates imply that foreign exchange intervention conducted by the Central Bank of Sri Lanka is consistent with its intention of not altering daily exchange rate returns. The view that the Central Bank of Sri Lanka does not focuss on a particular exchange rate target is further evident from the weak correlation between foreign exchange intervention with the exchange rate returns, as shown in the top panel of Appendix B.4.

Instead, the empirical estimates of the conditional mean equation suggests that the change in exchange rate returns is mainly determined by its own lagged value and the interest rate differential. A depreciation of the Sri Lankan rupee rate tends to further depreciate the exchange rate the next day. The coefficient of lagged exchange rate returns (β_{er}) is not only highly significant at the 1 percent level, but the magnitude is also relatively large (0.2 percent). Hussain and Jalil

(2007) and Shah et al. (2009), among others, found similar results for emerging economies. An increase in the first difference of the interest rate differential (β_d) leads the exchange rate to appreciate significantly. This is in line with the fact that the high interest rate differential should have attracted more capital inflows resulting in an appreciation of the exchange rate. Finally, an increase in the difference of the government bond spread is associated with an appreciation of the Sri Lankan rupee against prior expectations, but the magnitude is relatively small.

Effect on volatility of exchange rate returns All coefficients attached to intervention variables in the conditional volatility equation are negatively signed. It suggests that foreign exchange intervention by the Central Bank of Sri Lanka tends to reduce exchange rate volatility during the non-crisis period. However, only two-day lagged purchases and one-day lagged sales significantly reduce the volatility of exchange rate returns. Whether or not the Central Bank of Sri Lanka has been successful in curtailing excessive volatility in the rupee returns were only assessed through the signs and the statistical significance of the parameter estimates, as the economic significance of the effect of intervention on the conditional volatility is difficult to assess numerically under EGARCH model. The limitation is the non-differentiability of the absolute function $|z_{t-1}|$ at zero.

Although a rise in the interest rate differential is expected to reduce exchange rate volatility as a consequence of an increase in capital flows, the interest rate differential has a significant perverse effect, increasing the volatility of the exchange rate. This may be a result of investors' expectations on the overall macroeconomic environment of the country. Another possible reason is that a risk premium absorbing any appreciation pressure arises from positive interest rate differentials. Goyal and Arora (2010) found similar results for India when analyzing the effects of intervention. The bond spread, which reflects country risk, increases volatility in the domestic currency market.

The conditional variance of exchange rate returns is also affected by the direction of the shocks. The coefficient of θ, the asymmetry and leverage effects, is negative and statistically significant at the 1 percent level, and is between $-1 < \theta < 0$. This suggests that positive shocks increase volatility less than negative shocks. The decay rate that measures the persistent effects of the shocks

δ is close to 1, suggesting that shocks to the volatility of the exchange rate are persistent for a longer time during the non-crisis period, even if the central bank intervenes. The half-life statistic (Reyes, 2001) that estimates the time it takes to volatility to move halfway back to its mean level following a deviation from mean shows that a shock to the variance of the returns of the Sri Lankan rupee takes a minimum of 19 days $(\ln(0.5)/\ln(\delta))$ to halve its original size.

Joint significance of intervention through purchases and sales The Wald test investigates the joint significance of a subset of coefficients included in a model. Here, a Wald test is carried out to examine whether intervention through purchases and sales are jointly significant. Interestingly, the test statistics find strong evidence rejecting all null hypotheses, as shown in Table 4.4, suggesting that all intervention variables are jointly significant in explaining exchange rate returns as well as the volatility of exchange rate returns during the non-crisis period. The only exception is the test of joint significance of the sale of US dollars on exchange rate returns. These findings are in line with the parameter estimates presented in Table 4.3, where the coefficients of sales variables in the mean Equation, $\beta_{s,1}$ and $\beta_{s,2}$, are found to be insignificant. This confirms that intervention through sales does not have a significant effect on daily exchange rate returns.

Table 4.4: Joint Significance of Intervention through Purchases and Sales During the Non-crisis Period.

Null hypothesis	Test stat (p-value)
All intervention variables do not jointly affect daily returns	9.080
$\beta_{p,1} = \beta_{p,2} = \beta_{s,1} = \beta_{s,2} = 0$	(0.000)
Intervention through purchases does not jointly affect daily returns	18.031
$\beta_{p,1} = \beta_{p,2} = 0$	(0.000)
Intervention through sales does not jointly affect daily returns	0.122
$\beta_{s,1} = \beta_{s,2} = 0$	(0.885)
All intervention variables do not jointly affect volatility	31.674
$\gamma_{p,1} = \gamma_{p,2} = \gamma_{s,1} = \gamma_{s,2} = 0$	(0.000)
Intervention through purchases does not jointly affect volatility	3.513
$\gamma_{p,1} = \gamma_{p,2} = 0$	(0.030)
Intervention through sales does not jointly affect volatility	48.827
$\gamma_{s,1} = \gamma_{s,2} = 0$	(0.000)

Effectiveness of intervention The overall results suggest that foreign exchange intervention conducted by the Central Bank of Sri Lanka, examined through purchases and sales of US dollars, does not influence daily exchange rate returns, but reduce the conditional volatility of daily rupee returns during the non-crisis period. The empirical results reveal that the effect of intervention through purchases or sales on the conditional mean is not economically substantial. This, together with the effects of intervention on the conditional variance, which indicate that intervention reduces volatility in the daily rupee returns, suggest that the central bank has been successful in achieving its short- and medium-term targets of curtailing excess volatility and accumulating reserves, respectively. In summary, the empirical results suggest that foreign exchange intervention has been effective in Sri Lanka during the non-crisis period, and is consistent with the "leaning against the wind" policy to reduce volatility.

4.5.4 Effects of intervention during the crisis period

This Section examines the effectiveness of foreign exchange intervention by the Central Bank of Sri Lanka during the crisis period from July 02, 2007 to December 31, 2010, and the results are presented in Table 4.5.

Effect on exchange rate returns Parameter estimates of the conditional mean equation suggest that foreign exchange intervention through purchases and sales has statistically significant effects on daily exchange rate returns during the crisis period. Except for one-day lagged purchases ($\beta_{p,1}$), all other intervention parameters are against the prior expectation of the effects of intervention on exchange rate returns. However, this interpretation may be misleading as the effects of intervention are too small. As the value of parameter estimates suggests, a purchase of US dollars 100 million appreciates the Sri Lankan rupee/US dollar exchange rate by 0.009 percent within two days ($\beta_{p,1} + \beta_{p,2}$). A sale of US dollars 100 million depreciates the rupee by 0.16 percent within two days ($\beta_{s,1} + \beta_{s,2}$). In this context, intervention through purchases appreciates daily returns by an average of 0.001 percent, and intervention through sales depreciates the currency by an average of 0.02 percent within two days (See Table 4.1). However, the correlation between exchange returns and foreign exchange intervention during the crisis period presented in the bottom panel of Appendix B.4 is weak, again suggesting that the central bank does not target a particular level of the exchange rate.

As in the case of the non-crisis period, Sri Lankan rupee returns are mainly determined by the lagged value of exchange rate returns. Surprisingly, this Section finds no evidence to show that the interest rate differential has a significant effect on exchange rate returns during the crisis period. The reason for this may be partly attributed to the political and economic environment prevailing in the country, which discouraged the inflow of foreign exchange in addition to the financial crisis. However, increasing government bond spreads tends to depreciate the exchange rate during this period.

Effect on volatility of exchange rate returns The effect of interventions conducted by the Central Bank of Sri Lanka on the conditional volatility of the Sri Lankan rupee returns is not clear. In contrast to the effects during the non-crisis period, one-day lagged purchases ($\gamma_{p,1}$) and one-day lagged sales ($\gamma_{s,1}$) tend to increase exchange rate volatility. Though one-day lagged purchases do not have a significant effect on the conditional volatility, one-day lagged sales significantly increase volatility. Both two-day lagged purchases ($\gamma_{p,2}$) and two-day lagged sales ($\gamma_{s,2}$) reduce volatility in Sri Lankan rupee returns. These coefficients are found to be significant at the 1 percent level, reflecting the high explanatory power of this specification for the conditional volatility. This in turn suggests that intervention (both sales and purchases) reduces the volatility of daily rupee returns with lags of two days, although intervention through sales tends to increase volatility with one-day lag.

The interest rate differential does not play a significant role in the conditional volatility equation during the crisis period. Again, this may be due to the reduction in foreign exchange inflows as a result of domestic and global economic conditions prevalent during this period. The government bond spreads is still positively signed, suggesting that an increase in country risk increases volatility in the domestic foreign exchange market. The leverage effect term θ is positive and significant at the 10 percent level, indicating that the impact of a shock is asymmetric. The decay rate δ is less than that of the non-crisis period suggesting that the shocks to volatility of exchange rate returns are less persistent when the central bank increases its intervention in the foreign exchange market.[5] The half-

[5]As shown in Appendix B.1, the average intervention through purchases has increased from

Table 4.5: EGARCH (1,1) Model Parameter Estimates of the Crisis Period.

Parameter	EGARCH (1,1) Eq. (4.6), (4.9)
Conditional mean equation: coefficient(10^{-3})	
β_0	0.24 (0.883)
$\beta_{p,1}$	0.18 (0.000)
$\beta_{p,2}$	-0.27 (0.000)
$\beta_{s,1}$	0.19 (0.000)
$\beta_{s,2}$	1.43 (0.000)
β_d	-4.29 (0.616)
β_{sp}	0.29 (0.002)
β_{er}	107.07 (0.019)
Conditional variance equation: coefficient(10^{-3})	
ω	-820.82 (0.000)
$\gamma_{p,1}$	4.44 (0.109)
$\gamma_{p,2}$	-16.78 (0.000)
$\gamma_{s,1}$	31.38 (0.000)
$\gamma_{s,2}$	-43.47 (0.000)
γ_d	162.62 (0.308)
γ_{sp}	2.56 (0.018)
ARCH and GARCH terms	
α	0.758 (0.000)
δ	0.930 (0.000)
θ	0.039 (0.089)
Diagnostic test statistics	
$Q(20)$	37.683 (0.010)
$Q^2(20)$	15.931 (0.721)
LM	0.700 (0.497)
LogL	917.031
AIC	-2.122
BIC	-2.022

Note: The model is estimated over the period from July 02, 2007 to December 31, 2010 (see Equations (4.6) and (4.9)). The dependent variable in the mean equation is the Sri Lankan rupee returns. Total volumes of sales (sel_t) are included as negative values. Parameter estimates are multiplied by 1000. p-values are in parentheses.

life statistic indicates that a shock to volatility now takes only 9 days to reach half of its initial size.

Effectiveness of intervention Whether foreign exchange intervention conducted by the Central Bank of Sri Lanka has been successful during the crisis

US dollars 4.8 million in the non-crisis period to US dollars 16 million in the crisis period, while intervention through sales has increased from US dollars 6.6 million to US dollars 12.5 million.

period is an interesting question. As in the non-crisis period, foreign exchange intervention has not been influential in managing daily exchange rate returns during this period. The ambiguity is about the effect on conditional volatility. The fact that conditional volatility tends to increase by one-day lagged sales cannot be used to conclude that intervention is ineffective during this period. A significant reduction in volatility by two-day lagged purchases and two-day lagged sales may have a higher effect in offsetting the effects of one-day lagged sales.

Increased activities in the foreign exchange market suggest that the Central Bank of Sri Lanka has used intervention as a precautionary measure to prevent possible effects that could arise as a consequence of externally sourced negative shocks in the foreign exchange market during this period. The behavior of economic fundamentals that affect the foreign exchange market in the face of financial market turmoil may have undermined the effect of intervention during this period. Although the effect in reducing exchange rate volatility is not very strong, in general, foreign exchange intervention has been effective in Sri Lanka.

4.6 Conclusion

Using a unique data set on daily foreign exchange intervention, this Chapter investigated efficacy of foreign exchange intervention in emerging economies taking Sri Lanka as an example. For the estimation purpose, the total sample period was divided into two sub-periods: i) January 01, 2002 to June 29, 2007–"the non-crisis period" and ii) July 02, 2007 to December 31, 2010–"the crisis period". In the case of Sri Lanka, the crisis period corresponds to both the recent turbulence in global financial markets and the final stage of the country's civil war.

Comparing several GARCH specifications, the EGARCH(1,1) model was found to be the most appropriate framework to model the effects of foreign exchange intervention in Sri Lanka. The EGARCH methodology provides a convenient framework to gauge the effect of central bank intervention on the conditional mean and the variance of the Sri Lankan rupee/US dollar exchange rate. Additionally, it is not necessary to impose a non-negativity constraint on the parameters when the EGARCH methodology is applied. However, the main limitation of this methodology is being unable to quantify the effects on conditional volatility.

The empirical results found positive evidence on the effectiveness of foreign exchange intervention in Sri Lanka. The results indicate that foreign exchange intervention in Sri Lanka is consistent with the "leaning against the wind" policy to reduce volatility. This is true for both sub-periods, although the effect was not strong during the crisis period. Intervention, either through purchases or sales, has not been influential in managing daily returns of the Sri Lankan rupee returns. Thus, overall effect of foreign exchange intervention is consistent with the policy emphasis of the Central Bank of Sri Lanka, that is, accumulating international reserves and curtailing excessive volatility in the domestic foreign exchange market, without affecting the exchange rate trend.

The empirical findings of this Chapter are in line with Anand et al. (2011), who suggested that the Central bank of Sri Lanka attempts to curtail excess volatility, but are in contrast with their suggestion that intervention affects the exchange rate trend. The results are in line with Disyatat and Galati (2007), who revealed that foreign exchange intervention in emerging economies has little, if any, effect on exchange rate returns, but they have significant effects on curtailing excessive volatility.

The study found that the movements of Sri Lankan rupee returns are mainly determined by the lagged value of exchange rate returns. The effect of the government bond spread on exchange rate returns, though small, tends to increase exchange rate volatility during both sub-periods. The interest rate differential tends to appreciate the rupee during the non-crisis period, but does not have a significant effect during the crisis period. In the case of conditional volatility, the interest rate differential has a positive effect to increase volatility in the non-crisis period, but does has no significant effect in the crisis period. Additionally, the results found evidence for the existence of asymmetric volatility and leverage effect for the Sri Lanka rupee/US dollar exchange rate returns.

The empirical results suggest that intervention may be useful in containing unexpected short-term volatility in Sri Lankan rupee/US dollar exchange rate returns stemming from external shocks. The frequency of intervention and its success in reducing volatility suggest that there is a scope for emerging markets to operate flexible exchange rate regimes without having to adopt a pure float.

Future research in this field can be extended to estimate an expected loss function that depends on the deviation of the exchange rate from its long-term fundamental value, as well as on conditional volatility derived from the GARCH process. If the estimated loss function enables forecasts of out-of-sample intervention periods, it can be used as an effective rule for foreign exchange intervention by the central bank.

Chapter 5

Foreign Exchange Intervention and Volatility in Emerging Economies: A Latent Factor Approach

5.1 Introduction

This Chapter develops a new empirical framework based on the latent factor methodology to further investigate the effects of intervention for exchange rate volatility and reserve accumulation for emerging markets, using the case of Sri Lanka. The latent factor framework has not been previously applied to model foreign exchange intervention.[1] This class of models is often used to decompose financial market asset returns, particularly in currency and equity markets, into specified sources of volatility (Diebold and Nerlove, 1989; Mahieu and Schotman, 1994; Dungey, 1999).

This Chapter takes a set of currency returns of Sri Lanka and its major trading partners, as well as Sri Lankan intervention data from January 2002 to December 2010, as in Chapter 4, and models the variables as a function of global, idiosyncratic and intervention factors. The global factor affects all currency returns in the model but possibly in different ways. It captures movements in global

[1] Only one other manuscript, Aruman (2003) has considered intervention in a latent factor framework but uses a factor structure different to that adopted in this Chapter.

market fundamentals encompassing concepts such as, but not exclusively, global liquidity conditions and general trader risk aversion. An idiosyncratic factor is specified for each exchange rate return and captures movements specific to each of them. An intervention factor is specified in the Sri Lankan currency equation for days on which the Central Bank of Sri Lanka intervenes. Estimation is through Generalized Method of Moments (GMM).

The volatility decompositions are analyzed to understand the effects of intervention on Sri Lankan currency returns. If the contribution of the global and idiosyncratic factors is found to be the same across days with and without intervention, this suggests that foreign exchange intervention by the Central Bank of Sri Lanka is not effective in explaining the currency market volatility over the period under investigation. Alternatively, if the mechanisms vary across the two models, then the effectiveness of intervention can be assessed. Especially, the proposed model supplements the empirical analysis presented in Chapter 4 by assessing the effects of intervention on exchange rate return volatility, and examining its economic significance in the sense that the effect of intervention is large enough to explain currency market volatility.

The empirical results suggest that the central bank is successful in achieving its short- and medium-term objectives of containing exchange rate volatility and accumulating reserves, respectively. The central bank is able to influence overall foreign exchange return volatility by 5.5 percent during the period of relatively low volatility in foreign exchange markets before the recent crisis. On further delving into the effects of intervention, the data are split into days on which intervention occurs through purchases or sales of US dollars. Intervention is most effective when the bank purchases US dollars, suggesting that the Central Bank of Sri Lanka is successful in accumulating international reserves in line with the medium-term target as expected during a period of calm. The same model estimated for the crisis period presents strikingly different results. Sales of US dollars is more important this time with the central bank intervening to mitigate the exchange rate volatility in line with the short-term objective. Notably, the central bank tends to intervene in response to global factors rather than domestic (idiosyncratic) factors.

The rest of the Chapter proceeds as follows. Section 5.2 presents the exchange rate and intervention data that are used in the empirical application.

The modeling framework is developed in Section 5.3. Section 5.4 discusses the GMM estimation methodology that is adopted in this Chapter. The empirical results of the effect of foreign exchange intervention on exchange rate volatility are discussed in Section 5.5. This Section first focuses on the volatility decomposition for a factor model of exchange rate returns, and then extends this model to include intervention. The relative effect of purchases and sales of US dollars on currency return volatility is then examined. Finally, the model distinguishing purchases and sales is estimated for the crisis period corresponding to the recent crisis. Section 5.6 concludes.

5.2 Exchange Rates and Intervention Data

This Section presents a preliminary analysis of the data used in the model of foreign exchange intervention in Sri Lanka. The data comprise of $n = 5$ daily exchange rate returns of the euro (EUR_t), the Indian rupee (INR_t), the Japanese yen (JPY_t), the British pound (GBP_t) and the Sri Lankan rupee (SLR_t), expressed in US dollars, as well as daily net foreign exchange purchases by the Central Bank of Sri Lanka (INT_t). As in Chapter 4, exchange rate returns are computed by taking the first difference of the natural logarithm of the exchange rates and multiplying it by 100. Net foreign exchange purchases are in millions of US dollars. All series are demeaned and scaled by their respective standard deviations to express in standardized units.

The selection of exchange rates is based on Sri Lanka's main trading partner countries according to the weights assigned by the Central Bank of Sri Lanka in calculating the 24-currency real effective exchange rate. The top six countries' trade weights in the calculation of the real effective exchange rate are the US (19.74 percent), India (15.57 percent), the UK (9.86 percent), China (6.41 percent), Germany (5.88 percent) and Japan (4.99 percent), which form the basis of the sample selection.[2] As the focus is on countries with floating exchange rate regimes, some major trading partner currencies are excluded from the data set, including the Chinese yuan and the Malaysian ringgit, which operate under managed floating exchange rate regimes, and the Hong Kong dollar which is directly

[2]See Box Article 12 of the Central Bank of Sri Lanka Annual Report 2010, *Revision of Effective Exchange Rate Indices*, http://www.cbsl.gov.lk/pics_n_docs/10_pub/_docs/efr/annual_report/AR2010/English/9_Chapter_05.pdf (accessed June 5, 2011).

linked to the US dollar.[3] The sample consists of a selection of developed-market exchange rates, as well as the emerging-market exchange rate of the Indian rupee, which provides a convenient point of comparison with the Sri Lankan rupee in the model. The exchange rates and returns for Sri Lanka's major trading partners with floating exchange rates are shown in Figure 5.1. The outliers in the euro on March 1 and 2, 2005, as depicted in Figure 5.1, are removed using a dummy variable in the empirical analysis. An increase in the value of the exchange rate indicates an appreciation of the US dollar against the local currency.

As in Chapter 4, the sample period of this Chapter also extends from January 1, 2002 to December 31, 2010. For the estimation of the main empirical model in Section 5.5, the sample period is chosen to end on June 29, 2007 to avoid contaminating the analysis with the volatility in currency markets associated with the recent crisis in global financial markets. The model is then re-run for the high-volatility period in Section 5.5.4 to explore the effectiveness of intervention for emerging markets during periods of extreme volatility. Following the same terminology in Chapter 4, the first sub-period is labeled the "non-crisis period" and the latter "crisis period". The crisis sample period extends from July 2, 2007 to December 31, 2010, and is highlighted in the figures by the shaded regions.

Table 5.1 presents descriptive statistics on the Sri Lankan rupee and other exchange rate returns in the model for the total sample period, as well as for the two sub-periods. Table 4.1 in Chapter 4 presents similar statistics for the net intervention data. To re-cap, the intervention statistics are calculated for days on which the central bank intervenes in the currency market in any form. Graphical representations of the Sri Lankan rupee expressed in both (log) levels and returns, and net foreign exchange purchases data (intervention) for Sri Lanka are shown Figure 4.1 in Chapter 4. The greater volatility in magnitudes of intervention during the crisis period as shown in Table 4.1 and Figure 4.1 probably results from domestic and external factors as this period is not only coincides with the recent financial crisis, but also the final phase of the 25 year civil war in Sri Lanka.

[3]The Hong Kong Monetary Authority has guaranteed upper and lower bounds on the currency of US$1:HK$ 7.75 – 7.85 since May 18, 2005 (Source: Hong Kong Monetary Authority, http://www.hkma.gov.hk/eng/key-functions/monetary-stability/history-hong-kongs-exchange-rate-system.shtml (accessed June 5, 2011)).

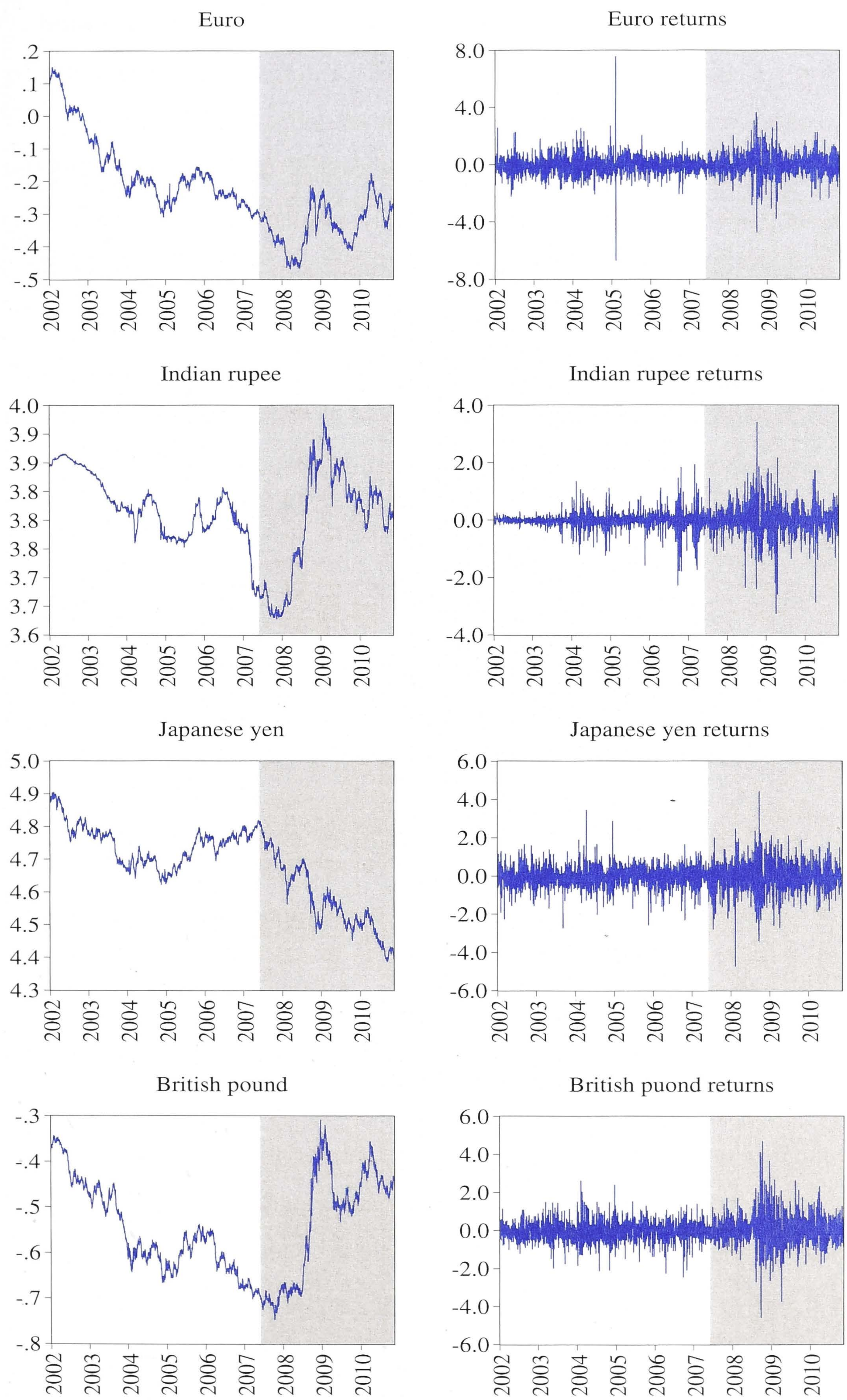


Figure 5.1: Daily Log Exchange Rates and Percentage Exchange Rate Returns, January 2002 to December 2010. Notes: Returns are for the euro, the Indian rupee, the Japanese yen and the British pound against the US dollar. The shaded area indicates the crisis period from July 2, 2007 to December 31, 2010 (Source: Central Bank of Sri Lanka).

Table 5.1: Descriptive Statistics of the Exchange Rate Returns (percent).

		Total sample			Non-crisis period			Crisis period		
Statistics	Variable	All	Non-int	Int	All	Non-int	Int	All	Non-int	Int
No. of obs.		2171	1089	1082	1324	763	561	847	326	521
Max	EUR	7.53	7.53	3.65	7.53	7.53	2.55	3.65	2.99	3.65
	INR	3.40	1.93	3.40	1.93	1.93	0.98	3.40	1.74	3.40
	JPY	4.41	3.44	4.41	3.44	3.44	1.29	4.41	2.47	4.41
	GBP	4.68	2.61	4.68	2.61	2.61	1.47	4.68	2.39	4.68
	SLR	1.25	1.15	1.25	1.15	1.15	0.77	1.25	1.14	1.25
Min	EUR	-6.69	-6.69	-4.73	-6.69	-6.69	-2.19	-4.73	-3.80	-4.73
	INR	-3.25	-3.25	-2.58	-2.26	-2.26	-1.57	-3.25	-3.25	-2.56
	JPY	-4.73	-2.71	-4.73	-2.71	-2.71	-2.56	-4.73	-2.21	-4.73
	GBP	-4.58	-2.71	-4.58	-2.46	-2.46	-2.08	-4.58	-2.71	-4.58
	SLR	-2.04	-2.04	-1.06	-2.04	-2.04	-1.06	-1.67	-1.67	-1.04
Mean	EUR	-0.02	-0.01	-0.03	-0.03	-0.03	-0.04	0.00	0.02	-0.01
	INR	-0.00	-0.01	-0.00	-0.01	-0.01	-0.02	0.01	-0.00	0.02
	JPY	-0.02	0.02	-0.06	-0.01	0.02	-0.04	-0.05	0.02	-0.09
	GBP	-0.00	-0.01	0.01	-0.02	-0.02	-0.03	0.03	0.01	0.04
	SLR	0.01	0.01	0.01	-0.01	0.01	0.01	0.00	0.00	-0.00
Std. dev.	EUR	0.75	0.77	0.73	0.69	0.75	0.59	0.84	0.81	0.85
	INR	0.43	0.44	0.42	0.31	0.35	0.24	0.57	0.58	0.56
	JPY	0.69	0.64	0.73	0.59	0.61	0.55	0.82	0.72	0.88
	GBP	0.69	0.64	0.74	0.56	0.60	0.50	0.86	0.75	0.93
	SLR	0.17	0.21	0.14	0.19	0.21	0.15	0.16	0.20	0.12

Note: The exchange rates are expressed in terms of US dollars. The statistics are calculated for each sub-period for all days (All), days on which there is no intervention (Non-int) and days on which there is intervention (Int). The total sample period is from January 1, 2002 to December 31, 2010, the non-crisis period is from January 1, 2002 to June 29, 2007, and the crisis period is from July 2, 2007 to December 31, 2010.

Net daily foreign exchange purchases are conducted only in the US dollar market; however, by doing so, the central bank indirectly influences the exchange rates of other currencies against the Sri Lankan rupee.[4] Table 5.1 shows that the Central Bank of Sri Lanka intervenes frequently. Over the sample period, intervention takes place on approximately 50 percent of all days, with a fairly even split between net purchases (547 days) and sales (535 days), as shown in Table 4.1. There is more intervention in the crisis period (62 percent of days) compared to the non-crisis period (43 percent of days).

Particular interest here is that, on days during the crisis period when the central bank intervenes, volatility is higher on intervention days than on days of no intervention for all countries excluding India and Sri Lanka. For example, on non-intervention days, the standard deviation of the euro is 0.81 percent compared to 0.85 percent on the intervention days, and increases from 0.75 percent to 0.93 percent for the pound. In contrast, the standard deviation for the Sri Lankan rupee falls from 0.20 percent to 0.12 percent perhaps suggesting that the central bank is effective in containing exchange rate return volatility through intervention when volatility is high, or perhaps reflecting the improvement of domestic conditions.

5.3 Factor Model Specification

The analytical framework employed in this paper is a latent factor model of exchange rate returns in the tradition of Diebold and Nerlove (1989), Mahieu and Schotman (1994), and Dungey (1999), where exchange rate returns are presented as functions of a set of independent latent factors. The factors in this application capture movements that are common to all exchange rate returns (global factors), idiosyncratic to each asset, and related to intervention. Adopting a factor structure has several advantages. First, the approach provides a parsimonious representation of the data. Second, observable variables do not have to be identified or modeled. Third, the approach is convenient to use, as the model implicitly takes into account all disturbances affecting the system of exchange rate returns. Finally, *i.i.d* and unit variance assumptions on the factor structure

[4]Note that changes in cross rates, for example between the Sri Lankan rupee and the euro, are not formally modeled in this Chapter, with all exchange rates expressed against the US dollar.

allow the decomposition of exchange rate returns into the contribution that each of the factors makes to overall volatility. The volatility decompositions are the main vehicle for this analysis.

In finalizing the factor model of central bank intervention, the model is built up in two stages. Section 5.3.1 specifies a factor model of exchange rate returns without formally modeling the effect of intervention. However, the model distinguishes between non-intervention and intervention days. On non-intervention days, exchange rate returns are a function of global and idiosyncratic factors. On intervention days, the exchange rate returns are a function of the same factors; however, the effect of each factor on each exchange rate return, as given by the factor loadings, is allowed to change through the formal modeling of structural breaks. These are designed to capture changes in the international and domestic dependence structures among the exchange rate returns which may be prevalent on the days that a central bank chooses to intervene in the foreign exchange market. The modeling of only the exchange rate returns in the first stage is to provide a sense of these dependence structures before the formal introduction of intervention.

In the second stage of modeling in Section 5.3.2, care is again taken to distinguish between non-intervention and intervention days. The intervention variable is introduced into the model of exchange rate returns and follows the same factor structure as the exchange rates, in that it is specified as a function of global and idiosyncratic factors. However, on intervention days, the Sri Lankan rupee exchange rate returns are allowed to be a function of the idiosyncratic factor associated with the intervention data. This model is able to provide evidence on the effectiveness of intervention by the Central Bank of Sri Lanka, as the contribution of intervention to the volatility of the exchange rate returns in comparison to the global and idiosyncratic factors is able to be assessed.

5.3.1 Model of exchange rate returns

This Section specifies a latent factor model of exchange rate returns, for intervention and non-intervention days, while suppressing the formal role for intervention. The model consists of n zero mean daily bilateral exchange rate returns expressed against the US dollar. The data set is separated into two parts, which aids identification as outlined in Section 5.4. Let e_t^0 denote the exchange rate returns on non-intervention days ($j = 0$), and let e_t^1 denote the exchange rate returns on intervention days ($j = 1$), such that:

$$e_t^j = \{EUR_t^j, INR_t^j, JPY_t^j, GBP_t^j, SLR_t^j\} \qquad j = 0, 1. \tag{5.1}$$

Non-intervention days The dynamics of the i^{th} exchange rate returns on non-intervention days ($j = 0$) is governed by a set of independent latent factors:

$$e_{i,t}^0 = \lambda_i^0 w_t + \gamma_i^0 u_{i,t} \qquad i = 1, 2, ..., n; j = 0. \tag{5.2}$$

There is a global factor in the model (w_t) that captures common shocks affecting each of the n exchange rate returns in the model with their own parameter loading λ_i^0. These global shocks are implicit in the data and capture global market fundamentals driving average currency returns and global financial market conditions such as liquidity or trader risk aversion in the global foreign exchange system.[5] The final factor $u_{i,t}$ is an idiosyncratic factor that captures shocks specific to each currency market, and reflects own-country fundamentals that are independent of global conditions. The loadings on the idiosyncratic factors are γ_i^0.

Intervention days On intervention days ($j = 1$), it is assumed that there is a possibility of higher volatility in the exchange rate market, perhaps prompting intervention. To allow for this, structural breaks in the factor structure are specified for intervention days. The dynamics of exchange rate returns for intervention days ($j = 1$) can be expressed as:

$$e_{i,t}^1 = (\lambda_i^0 + \lambda_i^1) w_t + (\gamma_i^0 + \gamma_i^1) u_{i,t} \qquad i = 1, 2, ..., n; j = 1 \tag{5.3}$$

where λ_i^1 and γ_i^1 are the structural breaks in the parameters on the global, numeraire and idiosyncratic factors.

[5] An alternative structure is to formally model a common numeraire factor to show that all returns are expressed in US dollars. This factor would affect each exchange rate return with a fixed loading in each equation. The presence of the numeraire factor imposes a no-arbitrage condition on the model, as shown in Dungey (1999). However, computationally, this specification did not work for this application.

In matrix form, the model of exchange rate returns can be expressed as:

$$\mathbf{e}_{\mathrm{t}}^{j} = \Lambda^{j}\mathbf{F}_{\mathrm{t}}, \tag{5.4}$$

where for intervention days $j = 1$

$$\begin{bmatrix} EUR_t^1 \\ INR_t^1 \\ JPY_t^1 \\ GBP_t^1 \\ SLR_t^1 \end{bmatrix} = \begin{bmatrix} (\lambda_1^0 + \lambda_1^1) \\ (\lambda_2^0 + \lambda_2^1) \\ (\lambda_3^0 + \lambda_3^1) \\ (\lambda_4^0 + \lambda_4^1) \\ (\lambda_5^0 + \lambda_5^1) \end{bmatrix} w_t$$
$$+ \begin{bmatrix} (\gamma_1^0 + \gamma_1^1) & 0 & 0 & 0 & 0 \\ 0 & (\gamma_2^0 + \gamma_2^1) & 0 & 0 & 0 \\ 0 & 0 & (\gamma_3^0 + \gamma_3^1) & 0 & 0 \\ 0 & 0 & 0 & (\gamma_4^0 + \gamma_4^1) & 0 \\ 0 & 0 & 0 & 0 & (\gamma_5^0 + \gamma_5^1) \end{bmatrix} \begin{bmatrix} u_{1,t} \\ u_{2,t} \\ u_{3,t} \\ u_{4,t} \\ u_{5,t} \end{bmatrix}. \tag{5.5}$$

Variance decompositions Using the assumption that the factors are $i.i.d.$ $(0, 1)$ random variables, Equations (5.2) and (5.3) can be used to express the volatility of each of the currency returns into its component factors. For intervention days:

$$\begin{aligned} Var\left(e_{i,t}^1\right) &= E[(e^1)_{i,t}^2] \\ &= (\lambda_i^0 + \lambda_i^1)^2 + (\gamma_i^0 + \gamma_i^1)^2. \end{aligned} \tag{5.6}$$

The proportion of the volatility of the return of exchange rate i when $j = 1$ explained by the global factor w_t, is:

$$\frac{(\lambda_i^0 + \lambda_i^1)^2}{(\lambda_i^0 + \lambda_i^1)^2 + (\gamma_i^0 + \gamma_i^1)^2}. \tag{5.7}$$

The proportion of the volatility of the return of exchange rate i explained by the idiosyncratic factor $u_{i,t}$, is:

$$\frac{(\gamma_i^0 + \gamma_i^1)^2}{(\lambda_i^0 + \lambda_i^1)^2 + (\gamma_i^0 + \gamma_i^1)^2}. \tag{5.8}$$

On non-intervention days ($j = 0$), the variance decompositions are the same, but with the structural break terms suppressed.

5.3.2 Model of central bank intervention

To examine the effectiveness of central bank intervention, the model in Section 5.3.1 is extended by introducing intervention (net purchases of US dollars) as an endogenous variable. The data set is again separated into two parts $(j = 0, 1)$, facilitating the identification of the effects of non-intervention vis-à-vis intervention days. Redefining e_t^j to consist of $n = 6$ series of zero mean bilateral exchange rates expressed against the US dollar, and a series of demeaned net intervention in millions of US dollars, the data set is:

$$e_t^j = \{EUR_t^j, INR_t^j, JPY_t^j, GBP_t^j, SLR_t^j, INT_t^j\} \qquad j = 0, 1. \tag{5.9}$$

The model for intervention in the Sri Lankan rupee exchange rate market rests on the assumption that intervention in Sri Lanka does not directly affect the exchange rate returns for the remaining exchange rates in the sample. Hence, the equations for the exchange rate returns for $n = 1, 2, ..., 4$ are the same as those stated in Equations (5.2) and (5.3).

The new variable, intervention $\left(INT_t^j\right)$, is explained by the first global factor w_t with parameter loading λ_{int}^j, and an idiosyncratic factor v_t with loading γ_{int}^j such that when $j = 0$

$$INT_t^0 = \lambda_{int}^0 w_t + \gamma_{int}^0 v_t, \tag{5.10}$$

and when $j = 1$

$$INT_t^1 = (\lambda_{int}^0 + \lambda_{int}^1) w_t + (\gamma_{int}^0 + \gamma_{int}^1) v_t.$$

The endogenous treatment of intervention and its inclusion when $j = 0$ provides a natural test of the model, as the variation in intervention is expected to be explained only by its own idiosyncratic factor, with no effect from the global factors.

The equation for the Sri Lankan rupee returns is the same as in Equation (5.2) for non-intervention days, but differs from Equation (5.3) for intervention days, where:

$$e_{5,t}^1 = (\lambda_5^0 + \lambda_5^1) w_t + (\gamma_5^0 + \gamma_5^1) u_{5,t} + \sigma_{int}^1 v_t. \tag{5.11}$$

The Sri Lankan rupee returns are now explained by the global factor w_t, and two idiosyncratic factors, $u_{5,t}$ and v_t. On intervention days, the factor v_t becomes an intervention factor, with the effectiveness of foreign exchange intervention by the central bank measured by the loading on the intervention factor in the Sri Lankan rupee exchange rate returns equation, σ^1_{int}.

In matrix form:

$$\mathbf{e}^j_\mathbf{t} = \Lambda^j \mathbf{F}_\mathbf{t}, \tag{5.12}$$

and the model of exchange rate returns can be expressed as:

$$\begin{bmatrix} EUR^1_t \\ INR^1_t \\ JPY^1_t \\ GBP^1_t \\ SLR^1_t \\ INT^1_t \end{bmatrix} = \begin{bmatrix} (\lambda^0_1 + \lambda^1_1) \\ (\lambda^0_2 + \lambda^1_2) \\ (\lambda^0_3 + \lambda^1_3) \\ (\lambda^0_4 + \lambda^1_4) \\ (\lambda^0_5 + \lambda^1_5) \\ (\lambda^0_{int} + \lambda^1_{int}) \end{bmatrix} w_t$$

$$+ \begin{bmatrix} (\gamma^0_1 + \gamma^1_1) & 0 & 0 & 0 & 0 & 0 \\ 0 & (\gamma^0_2 + \gamma^1_2) & 0 & 0 & 0 & 0 \\ 0 & 0 & (\gamma^0_3 + \gamma^1_3) & 0 & 0 & 0 \\ 0 & 0 & 0 & (\gamma^0_4 + \gamma^1_4) & 0 & 0 \\ 0 & 0 & 0 & 0 & (\gamma^0_5 + \gamma^1_5) & \sigma^1_{int} \\ 0 & 0 & 0 & 0 & 0 & (\gamma^0_{int} + \gamma^1_{int}) \end{bmatrix} \begin{bmatrix} u_{1,t} \\ u_{2,t} \\ u_{3,t} \\ u_{4,t} \\ u_{5,t} \\ v_t \end{bmatrix}. \tag{5.13}$$

when $j = 1$.

Volatility decompositions Analogous to the factor model of exchange rate returns, the volatility decompositions for the factor model of central bank intervention can be calculated using the expressions for the total variance for each type of variable:

$$\begin{aligned} Var(e^1_{i,t}) &= (\lambda^0_i + \lambda^1_i)^2 + (\gamma^0_i + \gamma^1_i)^2, \qquad i = 1, 2, ..., 4 \\ Var(e^1_{5,t}) &= (\lambda^0_5 + \lambda^1_5)^2 + (\gamma^0_5 + \gamma^1_5)^2 + (\sigma^1_{intv})^2, \\ Var(INT^1_t) &= (\lambda^0_{int} + \lambda^1_{int})^2 + (\gamma^0_{int} + \gamma^1_{int})^2. \end{aligned} \tag{5.14}$$

For the Sri Lankan rupee returns, the proportion of the volatility of the returns explained by the global factor w_t is:

$$\frac{(\lambda_i^0 + \lambda_i^1)^2}{(\lambda_i^0 + \lambda_i^1)^2 + (\gamma_i^0 + \gamma_i^1)^2 + (\sigma_{intv}^1)^2}. \tag{5.15}$$

The proportion of the volatility of the returns explained by its own idiosyncratic factor $u_{5,t}$ is:

$$\frac{(\gamma_i^0 + \gamma_i^1)^2}{(\lambda_i^0 + \lambda_i^1)^2 + (\gamma_i^0 + \gamma_i^1)^2 + (\sigma_{intv}^1)^2}. \tag{5.16}$$

Finally, the proportion of the volatility of the returns explained by the intervention factor v_t is:

$$\frac{(\sigma_{int}^1)^2}{(\lambda_i^0 + \lambda_i^1)^2 + (\gamma_i^0 + \gamma_i^1)^2 + (\sigma_{intv}^1)^2}. \tag{5.17}$$

In the same manner, the proportion of the volatility of intervention is decomposed into global (w_t) and idiosyncratic (v_t) factors, as:

$$\frac{(\lambda_{int}^0 + \lambda_{int}^1)^2}{(\lambda_{int}^0 + \lambda_{int}^1)^2 + (\gamma_{int}^0 + \gamma_{int}^1)^2}, \tag{5.18}$$

and:

$$\frac{(\gamma_{int}^0 + \gamma_{int}^1)^2}{(\lambda_{int}^0 + \lambda_{int}^1)^2 + (\gamma_{int}^0 + \gamma_{int}^1)^2}, \tag{5.19}$$

respectively.

5.4 GMM Estimation Method

As in Chapter 3, the factor models of exchange rate returns and central bank intervention specified in the previous Section use a GMM estimator. As alluded to in Section 5.3, the model of intervention is identified and estimated by exploiting the feature of the data that intervention did not occur on some days and did occur on others.[6] In the case of the factor model of central bank intervention, which contains $n = 6$ variables, there are a total of 42 moment conditions with which to identify 27 parameters by equating the empirical and theoretical moments of the model. Of the moment conditions, $((6 \times 7)/2) = 21$ derive from non-intervention day data, with the additional 21 derived from intervention day data.

The difference between the empirical moments and the theoretical moments

[6] Dungey et al. (2011) use the regimes of a non-crisis and a crisis period to identify models of contagion in much the same way that intervention is identified through the two regimes here of non-intervention days and intervention days.

of the model for each of the (non-intervention and intervention) regimes is:

$$M_0 = vech\left(\Omega^0\right) - vech\left(\Lambda^0\Lambda^{0\prime}\right), \tag{5.20}$$

and

$$M_1 = vech\left(\Omega^1\right) - vech\left(\Lambda^1\Lambda^{1\prime}\right), \tag{5.21}$$

where Ω^j refers to the empirical variance-covariance matrices for non-intervention and intervention days, and $\Lambda^j\Lambda^{j\prime}$ refers to the corresponding theoretical variance-covariance matrices for the two regimes. The Λ^j derives from equation (5.12) and uses the assumption that the factors are zero mean and unit variance, the empirical variance-covariance matrices are:

$$\Omega^j = \frac{1}{T_j}\sum_{t\in T_j} e_t^j e_t^{j\prime},$$

where T_j represents the sample size of the non-intervention and intervention day regimes.[7]

The objective function of the GMM estimator Q accounting jointly for both non-intervention days and intervention days is minimized according to:

$$Q = M_0^{\prime} W_0^{-1} M_0 + M_1^{\prime} W_1^{-1} M_1, \tag{5.22}$$

where W_j are the optimal weighting matrices that correct for heteroscedasticity corresponding to $j = 0, 1$. Note that in estimating the model, initial estimates of the variance-covariance matrices are obtained using identity weighting matrices. That is, $W_j = I$.[8] All calculations, including over-identification test (Hansen's J statistics), are undertaken using the same procedure described in Section 3.5 of Chapter 3.

[7]Attempts to identify the model described in Section 5.3 using the variance-covariance matrices of the total data set is infeasible, as this would generate only 21 empirical moments to identify 27 parameters in the theoretical model, leaving the model unidentified.

[8]For some variants of the models, the use of optimal weighting matrices was infeasible; thus, for consistency, results using the identity-weighting matrix for all models are reported.

5.5 Empirical Results

This section examines the effect of foreign exchange intervention by estimating the models outlined in Section 5.3. The first set of models are estimated for the low volatility period. Before estimating the fully specified model of central bank intervention in 5.5.2, a model of exchange rate returns without a formal role for intervention is first estimated in 5.5.1. The role of intervention is formally introduced in Sections 5.5.2 and 5.5.3. Section 5.5.2 evaluates the effectiveness of intervention in general, and Section 5.5.3 evaluates the differences in the effectiveness of intervention when the Central Bank of Sri Lanka intervenes by purchasing US dollars vis-à-vis when intervention occurs through sales. Finally, in Section 5.5.4, the model of central bank intervention distinguishing between purchases and sales is re-run over the global volatility sample period.

5.5.1 A factor model of exchange rate returns

The results of the factor model of exchange rate returns outlined in Section 5.3.1 are presented in Table 5.2. To recap, this model does not formally model intervention, but it does separate the data into non-intervention days and intervention days. The factor model of exchange rate returns is then estimated to examine the contribution of the global and idiosyncratic factors to the overall volatility in exchange rate returns for Sri Lanka (and other currencies) in the two sub-periods. The top panel of Table 5.2 provides the percentage contribution of the global and idiosyncratic factors to overall volatility on non-intervention days. The second panel provides the percentage contribution of the global and idiosyncratic factors to overall volatility on intervention days. The J-test for this model with 10 degrees of freedom is satisfied with a value of 13.481 and a p-value of 0.198.

The results provide interesting insights into overall movements in currency markets during the two regimes. On days when there is no intervention, the Sri Lankan rupee returns are dominated by the idiosyncratic factor with almost 100 percent of volatility purely domestic. Table 5.3 presents the parameter estimates for the factor model along with the p-values. On days when there is intervention, the volatility decomposition for Sri Lanka changes substantially. As shown in the second panel of Table 5.2, on intervention days, the global factor increases in importance from 0.2 percent to 15 percent. This suggests that Sri Lankan policy

Table 5.2: Volatility Decomposition of the Factor Model of Exchange Rate Returns.

	Factors	
	Global	Idiosyncratic
Non-intervention days ($j = 0$)		
EUR_t	41.983	58.017
INR_t	7.001	92.999
YEN_t	41.614	58.386
GBP_t	70.751	29.249
SLR_t	0.245	99.755
Intervention days ($j = 1$)		
EUR_t	39.999	60.001
INR_t	25.010	74.990
YEN_t	45.028	54.972
GBP_t	53.091	46.909
SLR_t	15.445	84.555

Note: Contribution to total volatility, in percent. The model is estimated over the period January 1, 2002 to June 29, 2007 (see Equations (5.7) and (5.8)).

makers respond to global movements rather than domestic (idiosyncratic) market specific movements, when intervening in currency markets. Providing further support to this view is that, on non-intervention days, the only insignificant parameter is the global factor for the Sri Lankan rupee returns (λ_5^0). Similarly, on intervention days, the only significant structural break parameter is the global factor for Sri Lanka (λ_5^1) (see Table 5.2). The analysis in Section 5.5.2 will provide further evidence on whether this is actually the case when intervention is formally introduced into the model.

On non-intervention and intervention days, the emerging economy of India is most similar to Sri Lanka, with 93 percent of its volatility a result of idiosyncratic factors on non-intervention days. On intervention days, the weight of the global factor is also larger for India, at 25 percent compared to 7 percent for non-intervention days. Global factors play a larger role for developed countries, with around 42 percent of volatility for the euro and yen returns, and 71 percent for the pound on non-intervention days.

5.5.2 A factor model of central bank intervention

The effects of intervention Estimating the factor model of central bank intervention, which adds an equation for intervention to the factor model of exchange

Table 5.3: Parameter Estimates of the Factor Model of Exchange Rate Returns.

	Global factors		Idiosyncratic factors	
	Parameters	Estimates	Parameters	Estimates
Non-intervention days ($j = 0$)				
EUR_t	λ_1^0	0.646	γ_1^0	0.760
		(0.000)		(0.000)
INR_t	λ_2^0	0.234	γ_2^0	0.855
		(0.000)		(0.000)
JPY_t	λ_3^0	0.668	γ_3^0	0.791
		(0.000)		(0.000)
GBP_t	λ_4^0	0.854	γ_4^0	0.549
		(0.000)		(0.000)
SLR_t	λ_5^0	-0.043	γ_5^0	0.873
		(0.460)		(0.000)
Intervention days ($j = 1$)				
EUR_t	λ_1^1	-0.289	γ_1^1	0.250
		(0.914)		(0.627)
INR_t	λ_2^1	-0.093	γ_2^1	-0.016
		(0.381)		(0.975)
JPY_t	λ_3^1	-0.036	γ_3^1	0.379
		(0.878)		(0.577)
GBP_t	λ_4^1	-0.178	γ_4^1	-0.003
		(0.358)		(0.986)
SLR_t	λ_5^1	-1.185	γ_5^1	-0.087
		(0.000)		(0.889)

Note: The model is estimated over the period January 1, 2002 to June 29, 2007 (see Equations (5.2) and (5.3)). p-values are in parentheses.

rate returns, does not change the volatility decomposition too dramatically, as shown by comparing Table 5.4 and Table 5.2. The equations for the currency returns in the factor model of central bank intervention remain the same as those in the factor model of exchange rate returns for all currencies apart from the Sri Lankan rupee (see Section 5.3.2). Inspection of the second panel of the volatility decomposition in Table 5.4 shows that the central bank is able to influence the volatility outcomes by 5.5 percent through intervention. This is an economically substantial magnitude given that the model is expressed in terms of daily returns. A comparison of this magnitude with the sample variance of the Sri Lankan rupee returns during this period (0.036 percent) provides further support for this view. Table 5.5 reports the results of Wald tests on the intervention parameters and the intervention terms are also statistically significant. Comparing the re-

Table 5.4: Volatility Decomposition of the Factor Model of Central Bank Intervention.

	Factors		
	Global	Idiosyncratic	Intervention
Non-intervention days ($j = 0$)			
EUR_t	44.039	55.961	-
INR_t	18.367	81.633	-
YEN_t	41.741	58.259	-
GBP_t	64.577	35.423	-
SLR_t	5.455	94.545	-
INT_t	0.010	99.990	-
Intervention days ($j = 1$)			
EUR_t	37.796	62.204	-
INR_t	30.425	69.575	-
YEN_t	40.812	59.188	-
GBP_t	48.183	51.817	-
SLR_t	16.782	77.697	5.521
INT_t	3.265	96.735	-

Contribution to total volatility, in percent. The model is estimated over the period January 1, 2002 to June 29, 2007 (see Equation (5.13)).

sults from the factor model of exchange rate returns (Table 5.2) to the model of central bank intervention (Table 5.4) for Sri Lanka shows that in both models, global factors contribute around 16 percent to Sri Lankan rupee return volatility. The intervention factor absorbs some of the volatility that is attributed to the idiosyncratic factor in the previous model. Note that all of the structural break parameters in the model are jointly significant as shown in Table 5.5.

The biggest difference in the results for the currency returns between the two models is in the contribution of the global factor on non-intervention days to the returns of India and Sri Lanka. For India, the contribution of the global factor rises from 7 percent to 18 percent; for Sri Lanka, it rises from 0.2 percent to 5.5 percent. These increases in magnitude suggest that the inclusion of Sri Lankan central bank intervention in the model now places greater weight on the emerging markets in the global factor and alludes to some linkages between India and Sri Lanka.

The inclusion of an intervention equation provides a natural test of the model. On non-intervention days, it is expected that the idiosyncratic factor for the intervention equation should dominate, as nothing is happening in the intervention data on these days. This is indeed the case, with the idiosyncratic intervention factor explaining 99.99 percent of the volatility in intervention data on non-intervention days. Finally, the model of central bank intervention provides a good overall fit to the data, with the value of the J-test of 0.120.

Table 5.5: Wald Tests of Intervention and Structural Breaks in the Factor Model of Central Bank Intervention.

Hypothesis	DOF	Test statistic	p-value
Joint intervention parameters	2	90.248	0.000
$H_0 : \sigma^1_{int} = \gamma^1_{int} = 0$			
Joint idiosyncratic and intervention parameters	3	69.368	0.000
$H_0 : \gamma^0_{int} = \sigma^1_{int} = \gamma^1_{int} = 0$			
Joint structural break parameters	12	2270.097	0.000
$H_0 : \lambda^1_i = \gamma^1_i = 0, \qquad i = 1, 2, ..., 6$			

Note: The model is estimated over the period January 1, 2002 to June 29, 2007 (see Equation (5.13)).

5.5.3 Purchases versus sales

To further investigate the effectiveness of intervention, the intervention data are split into days when the Central Bank of Sri Lanka intervenes by purchasing US dollars, and days when intervention occurs through sales. The model for intervention days is written as:

$$e^+_{5,t} = (\lambda^0_5 + \lambda^+_5)w_t + (\gamma^0_5 + \gamma^+_5)u_{5,t} + \sigma^+_{int}v^+_t. \tag{5.23}$$

where $+$ denotes days of US dollar purchases; and:

$$e^-_{5,t} = (\lambda^0_5 + \lambda^-_5)w_t + (\gamma^0_5 + \gamma^-_5)u_{5,t} + \sigma^-_{int}v^-_t. \tag{5.24}$$

where $-$ denotes days of US dollar sales. Hence, the factor model is jointly estimated in three parts rather than two, and this model again satisfies the J-test with 25 degrees of freedom and a p-value of 0.921.

Table 5.6 presents the volatility decomposition for the three regimes. The results clearly indicate that the central bank is more effective on days of US dollar purchases (sales of Sri Lankan rupee), with 11 percent of volatility in the Sri Lankan rupee returns being due to the central bank volatility. In contrast, on

Table 5.6: Volatility Decomposition of the Factor Model of Central Bank Intervention Distinguishing Between Intervention through Purchases and Sales of US Dollars During the Non-crisis period..

	Factors		
	Global	Idiosyncratic	Intervention
Non-intervention days ($j = 0$)			
EUR_t	44.386	55.614	-
INR_t	18.349	81.651	-
YEN_t	41.547	58.453	-
GBP_t	63.083	36.917	-
SLR_t	5.698	94.302	-
INT_t	0.000	100.000	-
Days of purchases ($j = +$)			
EUR_t	28.033	71.967	-
INR_t	41.976	58.024	-
YEN_t	39.258	60.742	-
GBP_t	39.272	60.728	-
SLR_t	22.183	67.004	10.813
INT_t	2.583	97.417	-
Days of sales ($j = -$)			
EUR_t	36.253	63.747	-
INR_t	28.499	71.501	-
YEN_t	41.472	58.528	-
GBP_t	0.000	100.000	-
SLR_t	17.225	80.722	2.053
INT_t	4.104	95.896	-

Note: Contribution to total volatility, in percent. The model is estimated over the period January 1, 2002 to June 29, 2007.

days of sales of US dollars (purchases of Sri Lankan rupee), intervention is less effective and explains only 2 percent of volatility. This result is consistent with the empirical findings for the non-crisis period presented in Chapter 4, where intervention through purchases has more effect in reducing Sri lankan rupee/US dollar exchange return volatility compared to intervention through sales. This suggests that the Central Bank of Sri Lanka is more successful in influencing the exchange rate when the pressure in currency markets is to appreciate the Sri Lankan rupee. This result also indicates that the Central Bank of Sri Lanka is also focussed on achieving its medium-term target of accumulating international reserves.

It is worth commenting on the changing role of the Indian rupee in this model.

On days when intervention occurs, through either purchases or sales, the global factor affects Indian rupee returns by substantially more than on non-intervention days, again alluding to a possible common factor between India and Sri Lanka.

5.5.4 Intervention in the crisis period

The first objective of the central bank is to contain excessive volatility in the exchange rate in the short-run. This objective is examined in this Section using the crisis period corresponding to the recent financial crisis. Intuitively, it is expected that increased volatility in currency markets will lead to more intervention as monetary authorities move to curb some of the volatility. This is verified in Table 5.1, which presents statistics on intervention during the crisis period of July 2, 2007 to December 31, 2010. There are proportionately more days when intervention took place in the crisis period, and the standard deviation of intervention is also higher. Notably, the number of intervention days through sales of US dollars is higher than the number of days of purchases, suggesting that the central bank aims to prevent excess currency market volatility arising from negative short-run shocks (or those placing pressure on the currency to depreciate), such as those of the recent financial crisis.

The model in Section 5.5.3, which distinguishes the effects of intervention through the purchases and sales of US dollars, is estimated for the period July 2, 2007 to December 31, 2010. The results reinforce the suggestion that the Central Bank of Sri Lanka is successful in meeting its first objective of containing excessive currency market volatility in the short-run, particularly when pressure is for a rupee depreciation. Table 5.7 shows the volatility decomposition corresponding to this period, and it clearly indicates that central bank intervention is more effective on days of US dollar sales than on days of purchases, with 11 percent of volatility in Sri Lankan rupee returns due to central bank intervention. In contrast, on days of purchases, intervention explains only 3 percent of total volatility. The sample variance of the Sri Lankan rupee returns during the crisis period is 0.026 percent, revealing that central bank intervention explains a substantial portion of the currency market variance. These findings further confirm the results presented in Chapter 4.

The results for the crisis period are in contrast to the non-crisis period, where

Table 5.7: Volatility Decomposition of the Factor Model of Central Bank Intervention Distinguishing Between Intervention through Purchases and Sales of US Dollars during the Crisis Period.

	Factors		
	Global	Idiosyncratic	Intervention
Non-intervention days ($j = 0$)			
EUR_t	79.921	20.079	-
INR_t	12.583	87.417	-
YEN_t	3.641	96.359	-
GBP_t	59.704	40.296	-
SLR_t	3.898	96.102	-
INT_t	4.093	95.907	-
Days of purchases ($j = +$)			
EUR_t	65.314	34.686	-
INR_t	29.451	70549	-
YEN_t	2.650	97.350	-
GBP_t	51.721	48.279	-
SLR_t	15.384	82.210	2.406
INT_t	0.823	99.177	-
Days of sales ($j = -$)			
EUR_t	58.055	41.945	-
INR_t	24.616	75.384	-
YEN_t	2.042	97.958	-
GBP_t	0.000	100.000	-
SLR_t	4.170	84.649	11.181
INT_t	3.399	96.601	-

Note: Contribution to total volatility, in percent. The model is estimated over the period July 2, 2007 to December 31, 2010.

purchases of US dollars are more effective than sales. Intervention during the crisis period on days of purchases is consistent with the model for the non-crisis period, which sees the global factor increase in importance for overall volatility compared with non-intervention days. On days of purchases, the global factor does not change by much, with most of the intervention absorbed from the idiosyncratic factor, which falls from around 96 percent to 85 percent during this time.[9]

[9] Although this paper does not focus on changes to the decompositions for the remaining countries in the sample, it is to glean an insight into the crisis period and the dynamics of the currency markets during this time. The results differ markedly in terms of decompositions for most currencies in the model in the crisis period, particularly for the euro and yen. The global factor now contributes 80 percent to the euro exchange rate volatility on non-intervention days, reflecting that the euro US dollar relationship is a key source of volatility. Similarly, the yen is now completely driven by idiosyncratic factors (96 percent).

5.6 Conclusion

Foreign exchange intervention by central banks in emerging economies has only been studied to a limited extent, and the effects of such intervention is not well understood. This Chapter contributes to this literature by estimating a latent factor model of central bank intervention for the emerging economy of Sri Lanka. The factor structure provides a convenient method of identifying sources of currency market volatility by decomposing currency returns of Sri Lanka and its major trading partners into a set of factors that includes global, idiosyncratic and intervention factors. An advantage of latent factors is that observable variables do not need to correspond particularly to global and idiosyncratic factors. The effectiveness of intervention was assessed over two periods: first is the non-crisis period corresponding to the relatively tranquil period in global financial markets, from January 2002 to June 2007; second is the crisis period corresponding to the recent financial crisis, from July 2007 to December 2010.

The empirical results are supportive of intervention being effective in Sri Lanka over the two periods, albeit in different ways. The results during both periods show that the Central Bank of Sri Lanka responds to global movements in currency markets when they intervene, rather than movements specific to the domestic foreign exchange market, suggesting that the central bank attempts to shield the domestic economy from externally sourced fluctuations. Comparing volatility decompositions of the factor models of exchange rate returns and central bank intervention for Sri Lanka suggests that, through intervention the central bank has been able to influence volatility by 5.5 percent of the total over the non-crisis period.

Extending the analysis to capture the varying effects of intervention through purchases or sales of US dollars clearly shows that the central bank is more effective on days of US dollar purchases during the non-crisis period. Eleven percent of total volatility is explained by intervention through purchases, compared to only 2 percent of volatility in the case of intervention through sales of US dollars. These findings are consistent with the medium-term objective of the Central Bank of Sri Lanka of accumulating foreign exchange reserves, suggesting successful reserves management between 2002 and 2007.

In contrast to the dominance of intervention through purchases relative to sales for the non-crisis period, the central bank is focused on mitigating excess currency market volatility arising from perceived short-run shocks such as those of the recent global financial crisis. The variance decompositions calculated for the period from 2007 to 2010 clearly show that 11 percent of Sri Lankan currency market volatility is explained by sales of US dollars as the central bank attempted to absorb some of the global turmoil in currency markets through exchange rate management.

A comparison of the relative contributions of the intervention factor with the sample variances further reveals that the effect of intervention by the Central Bank of Sri Lanka in reducing excess volatility of the Sri Lankan rupee returns is economically substantial in both sample periods, complimenting the results found in Chapter 4.

In the policy context, understanding the sources of exchange rate volatility specific to the domestic currency market enables the central bank to use its intervention policy effectively. For example, if the central bank limits intervention to specific moments, such as in periods of financial market turmoil, intervention could play a useful role in containing the adverse effects of transitory shocks on financial stability. Although intervention is found to be effective, it will be interesting to examine whether official reserves have been effectively used by the Central Bank of Sri Lanka when intervening in the foreign exchange market.

Chapter 6

Concluding Remarks

6.1 Summary

The main objective of this thesis was to study the analytical and empirical aspects of the financial market volatility during the crisis of 2007-2011. The world economy has become increasingly integrated during the last few decades. Therefore, a shock that occurs in one part of the global economy quickly transmits to the other markets across national borders through multiple channels, both direct and indirect. The crisis of 2007-2011 is one such event. Although past experiences led a financial crisis to be thought of as a phenomenon attached to emerging economies, the recent crisis, which originated in the core of the world economy, has changed that belief. The financial crisis, which first unfolded in the US sub-prime mortgage market in mid-2007, spread across asset markets in developed countries, and quickly reached unprecedented levels, generally leaving emerging markets as a success story. The transmission of the effects of the crisis was largely unforeseen, and has forced a rethinking of financial market volatility and global financial linkages. These circumstances constituted the motivation for this thesis.

This thesis consisted of two parts. The first part, comprised of Chapters 2 and 3, investigated the mechanisms of volatility transmission across financial markets in developed countries. Specifically, Chapter 2 captured the transmission mechanism of the recent crisis, driven by the changes in carry traders' behavior, by using a global game approach. Chapter 3 investigated the volatility transmission mechanism during the crisis of 2007-2011 by using a latent factor model of cross-country and cross-market financial contagion. The second part, comprised of Chapters 4 and 5, evaluated the efficacy of foreign exchange intervention, which is one of the primary policy tools used by central banks to shield against external shocks, particularly in emerging economies. Additionally, the sources of exchange rate volatility with and without central bank intervention were identified; and the economic significance of the effects of foreign exchange intervention was assessed. Two macroeconometric methodologies, the generalized autoregressive heteroskedasticity (GARCH) and the latent factor methodology were applied in this context.

6.2 Main Findings

This Section summarizes the main findings that emerged from this in terms of three different themes: herd behavior of international investors, financial market contagion and foreign exchange intervention.

Herd behavior Herding is one among several explanations given for the spread of market turmoil. Chapter 2 developed an analytical model to investigate how the recent crisis was realized in an investment recipient country as a result of unwinding of carry trades, which were induced by credit crunches in major funding countries. However, this framework is not limited to the crisis of 2007-2011, or the carry traders' behavior, rather, can be used as a model to explain shocks attributed to any financial crisis. The model shows that carry traders receive signals about margin constraints or the haircut. As this information is not perfect, these noisy signals lead some carry traders to unwind their positions. Consequently, the cost for the other carry traders to roll over their investment increases, resulting increased number of withdrawals. This suggests that carry traders adjust their decisions depending on the information derived from observing others' actions.

This study found that there is a threshold level of the "haircut" or margin constraint, on which investors' decisions on unwinding carry positions are made. Sudden changes in the behavior of carry traders lead the investment country to sell its illiquid assets, forcing the exchange rate to depreciate. The more the carry traders unwind their positions, the more the sale of assets in the recipient country.

This tends to decline the asset prices sharply, while repayment to carry traders forces the exchange rate to depreciate. Finally, the model shows how a financial crisis transmitted to the investment recipient country, shifting its economy to a bad equilibrium even though it was not initially threatened by the crisis. That is, due to the herding behavior of carry traders, and feedback effects of asset prices and exchange rates holding during the financial crisis, the financial markets increasingly become destabilized.

Financial contagion The presence of common international investors who change their investment positions in the face of a financial market turmoil is one channel of the volatility transmission mechanism from one asset market to another. Existing literature on financial crises has often suggested that there are other mechanisms for contagion through which financial market turbulence spreads across national borders. This argument constituted the basis for studying the relative importance of the contagion transmission mechanisms across countries and markets, during the recent crisis.

Chapter 3 extended the analysis of the transmission of the financial crisis to investigate the contagion transmission mechanism across equity and bond markets in an empirical setting. A latent factor model was developed to decompose volatility of excess asset returns into common, market, country, idiosyncratic and contagion factors, assuming that contagion effects were spreading through the additional transmission mechanisms generated in the market and idiosyncratic components during the crisis period. Five countries—Australia, Europe, Japan, the UK and the US—were included in the empirical study in order to cover a range of developed financial markets.

The empirical results found that the crisis of 2007-2011 was highly contagious. Investigation of the three phases of the crisis—the US sub-prime crisis, the global financial crisis and the European debt crisis—found that contagion was highly prevalent in both classes of asset markets in all three phases of the crisis. That is, developed country asset markets were vulnerable to shocks attributed to all three phases of the crisis. However, the contagion transmission mechanisms dynamically changed during the three phases, and were found to vary depending on the phase and the source of the crisis. Bond markets were affected by the shocks originated in the global equity market, however, the reverse exists only to a lesser extent. In line with the leading role play by the US financial markets in the global economy, the additional links from the US financial markets contributed to the financial market contagion. However, the relative importance of these US idiosyncratic asset market channels changed across markets and across the three phases of the crisis.

Foreign exchange intervention Investigation of the effectiveness of policy instruments that aim to stabilize the foreign exchange markets is another important aspect of studying the crisis transmission. Chapters 4 and 5 analyzed the effectiveness of foreign exchange intervention, with the focus on emerging economies. The experience of the Central Bank of Sri Lanka provided the basis for these analyses. Chapter 4 applied the GARCH methodology, which is commonly used in modeling financial time series that exhibit time-varying volatility clustering to understanding the effects of intervention on the exchange rate and also on the volatility of the exchange rate. The empirical results found evidence for the existence of asymmetric volatility and leverage effect for the Sri Lankan rupee/US dollar exchange rate returns. Further, it found that the Central Bank of Sri Lanka has enacted a "leaning against the wind" policy to reduce currency market volatility, rather than influencing the exchange rate trend. Most importantly, the results showed that the Central Bank of Sri Lanka was successful in achieving its short-term objective of curtailing excessive volatility in the currency market, and its medium-term objective of accumulating international reserves. Although the effect of intervention in reducing volatility seemed to be lower during the crisis period compared to the non-crisis period, this conclusion requires further quantification and explanation, as difficulties arise in measuring the economic significance of the effects of intervention, which is a main limitation of this study.

Chapter 5 extended the analysis to further explore the effectiveness of foreign exchange intervention by identifying the sources of exchange rate volatility, and also investigating the economic significance of the effects on the foreign exchange market as the central bank intervenes. This study was novel in that it applied a latent factor framework in the context of exchange rate volatility with foreign exchange intervention. The empirical results give several insights. Although the domestic market specific factors were found to be dominant in explaining exchange rate volatility, the results suggest that Sri Lankan policymakers were responding to the global movements in currency markets when intervening, rather than movements specific to the domestic foreign exchange market. By comparing the relative sizes of the intervention factor with the variance of daily exchange rate returns, this analysis further suggest that the effects of foreign exchange intervention constituted an economically substantial effect on the currency market volatility. Importantly, the results claim that foreign exchange intervention was successful in accumulating international reserves during the non-crisis period, while reducing volatility during the crisis period.

6.3 Policy Implications

With the effects of the recent financial crisis which are still unfolding, the findings of this thesis highlight a number of policy implications. Overall, the results presented in Chapters 2 and 3 suggest some policies for the stabilization of the international financial system. The results reveal that mature financial markets are also vulnerable to financial crises, though such crises were previously thought to be a feature only of emerging markets. The results that emerged in Chapter 2 highlight the need to implement adequate supervisory and regulatory mechanisms, and emphasize the need to control the extent of currency and maturity mismatches of financial institutions in order to prevent the adverse effects of sudden capital flights, that is a characteristic of the unwinding of carry trades.

The vulnerability of developed asset markets to financial contagion, and the dynamics of the contagion transmission mechanisms across different phases of the crisis—as highlighted in Chapter 3—emphasize the need to develop better contingency plans to manage systematic failures. Such contingency plans should account for all the aspects of the crisis, including contagion effects that may go beyond a country's own economy. They should also take into account the relative importance of the channels through which contagion transmit over different phases of the crisis.

The conclusions drawn in Chapters 4 and 5 lead to some important policy implications in relation to exchange rate and central bank intervention, particularly in the context of emerging economies. The results in both Chapters found evidence for the effectiveness of foreign exchange intervention in Sri Lanka.

The empirical results suggest that intervention is useful in containing unexpected short-term volatility stemming from external shocks, while accumulating international reserves in the medium-term. The frequency of intervention and its success in reducing volatility suggest that there is some possibility for emerging markets to operate flexible exchange rate regimes without having to adopt a pure float.

Further, designing appropriate policies to reduce excess volatility in the foreign exchange market with the understanding of the sources specific to the domestic currency market will enable the central bank to use its intervention policy effectively. For example, if the central bank intervene at specific events—such as recent crisis in global financial markets—intervention could play a useful role in containing the adverse effects of transitory shocks on financial stability.

6.4 Future Research Directions

The findings of this thesis open new avenues for future research. Chapter 2 of the thesis developed an analytical framework to analyze the transmission of the recent financial crisis through of unwinding of carry trades driven by the changes in investors' behavior. The proposed model could be further validated by testing on the real financial market data, although, collecting data on margins or haircut might be a challenge. Another potential direction for future research is extending the analytical framework to introduce dynamical behavior of exchange rate and asset price.

The empirical analysis on financial market contagion presented in Chapter 3 can be further extended by capturing how the relative strength of financial contagion affected when the benchmark asset market is the source of the shock. Focusing on the period of the US sub-prime mortgage crisis, Dungey (2008) has attempted to capture this phenomenon by developing a factor model. The future research along this line could be extended with the basis provided by Dungey (2008); although incorporating both the US originated crisis as well as the European debt crisis will be challenging. Extending the empirical analysis to include a set of emerging market economies will improve the model by enabling a distinction of the contagion effects between developed and emerging economies. It could be used to assess whether the emerging markets were immune to the effects of contagion during the crisis of 2007-2011. A larger country set will also enable identification of the effects of more factors, such as emerging market factors and/or regional factors.

The findings in Chapters 4 and 5 suggest some potential areas of research in the context of foreign exchange intervention. An interesting exercise in this context would be to estimate an expected loss function that depends on the deviations of the exchange rate from its long-term fundamental value, and the conditional volatility of the exchange rate. When "excessive exchange rate volatility" is not defined explicitly, this estimated loss function could be used as the effective rule governing foreign exchange intervention by the central bank, if it is able to produce out-of-sample forecasts. As intervention is a costly measure for any central bank, another potential area of research would be to investigate whether foreign exchange reserves are effectively used when intervening in the foreign exchange market.

Appendix A

Chapter 3 Appendices

A.1 Data Description and Sources

Country	Description	Datastream Code
Australia	S&P/ASX 200 stock market index	ASX200I
	10 years benchmark bond yield	AUBRYLD
	Australian dollars per US dollar	AUSTDO$
Germany	German DAX price index	DAXINDX
	10 years government bond yield	GBBD10Y
	Euro per US dollar	EMUSDSP
Greece	FTSE/ATHEX 20 price index	FTASE20(PI)
	10 years benchmark bond yield	GRBRYLD
Italy	FTSE MIB price index	FTSEMIB(PI)
	10 years benchmark bond yield	ITBRYLD
Japan	Nikkei 225 stock price index	JAPDOWA
	10 years benchmark bond yield	JPBRYLD
	Japanese yen per US dollar	JAPYNUS
UK	UK FTSE all share price index	FTALLSH(PI)
	10 years government bond yield	GBUK10Y
	British pound per US dollar	BRITPUS
US	DOW JONES industrial price index	DJINDUS(PI)
	Corporate BAA bond yield	FRCBBAA
	Risk free 10 year benchmark bond yield	USBD10Y

A.2 Non-crisis Factor Contributions

Country	Factor	Phase I		Phase II		Phase III	
		Equity	Bond	Equity	Bond	Equity	Bond
AU	Common	20.82	63.58	15.67	70.11	19.46	65.54
	Equity market	29.93	n.a.	37.09	n.a.	33.23	n.a.
	Bond market	n.a	3.27	n.a.	0.05	n.a.	2.47
	Country	8.80	3.56	2.88	14.47	24.57	1.21
	Idiosyncratic	40.45	29.59	44.36	15.37	22.74	30.78
EU	Common	21.57	37.04	16.70	49.52	18.26	36.61
	Equity market	45.16	n.a.	50.38	n.a.	50.92	n.a.
	Bond market	n.a	45.65	n.a.	36.91	n.a.	49.17
	Country	1.02	17.30	1.22	10.24	4.46	5.34
	Idiosyncratic	32.25	0.01	31.69	3.33	26.36	8.88
JP	Common	12.20	62.91	8.46	68.94	10.66	65.21
	Equity market	22.03	n.a.	31.28	n.a.	24.91	n.a.
	Bond market	n.a.	8.98	n.a.	3.05	n.a.	7.05
	Country	48.88	4.67	41.75	4.61	49.09	4.05
	Idiosyncratic	16.89	23.44	18.51	23.39	15.35	23.70
UK	Common	16.59	25.47	13.51	37.30	14.72	26.81
	Equity market	69.67	n.a.	70.08	n.a.	67.58	n.a.
	Bond market	n.a	50.55	n.a.	32.25	n.a.	42.96
	Country	0.71	23.66	0.29	30.43	2.26	8.81
	Idiosyncratic	13.03	0.32	16.11	0.02	15.44	21.42
US	Common	40.52	82.85	34.74	84.19	38.06	79.29
	Equity market	11.10	n.a.	15.61	n.a.	12.80	n.a.
	Bond market	n.a	4.43	n.a.	0.41	n.a.	3.94
	Country	0.47	12.72	0.12	15.34	34.84	0.62
	Idiosyncratic	47.91	0.00	49.53	0.02	14.30	16.15

Note: The volatility decomposition is presented as a percentage of total volatility. n.a. denotes not applicable.

A.3 Volatility Decomposition of Non-contagion Components During the Crisis Period

Country	Channel	Phase I		Phase II		Phase III	
		Equity	Bond	Equity	Bond	Equity	Bond
AU	**Non-contagion**	**24.28**	**90.37**	**29.36**	**61.52**	**52.81**	**48.25**
	Common	4.40	31.33	0.59	12.13	1.48	28.49
	Equity market	9.48	n.a.	27.01	n.a.	47.74	n.a.
	Bond market	n.a.	42.71	n.a.	44.23	n.a.	5.86
	Country	1.86	1.75	0.11	2.50	1.86	0.53
	Idiosyncratic	8.54	14.58	1.66	2.66	1.73	13.38
EU	**Non-contagion**	**18.86**	**65.31**	**8.08**	**40.55**	**71.54**	**72.13**
	Common	7.38	16.75	0.85	6.32	1.79	23.02
	Equity market	0.10	n.a.	5.55	n.a.	68.93	n.a.
	Bond market	n.a	40.74	n.a.	32.50	n.a.	19.37
	Country	0.35	7.82	0.06	1.31	0.44	3.36
	Idiosyncratic	11.03	0.00	1.61	0.42	0.17	26.39
JP	**Non-contagion**	**71.49**	**76.37**	**67.94**	**33.27**	**42.29**	**35.05**
	Common	5.59	29.78	0.69	8.65	1.98	23.38
	Equity market	33.86	n.a.	62.30	n.a.	28.30	n.a.
	Bond market	n.a.	34.29	n.a.	21.11	n.a.	1.72
	Country	23.59	2.21	3.42	0.58	9.15	1.45
	Idiosyncratic	8.15	11.09	1.52	2.94	2.86	8.50
UK	**Non-contagion**	**4.41**	**82.52**	**21.06**	**68.43**	**64.06**	**34.87**
	Common	3.29	9.87	0.37	5.29	0.74	12.56
	Equity market	0.05	n.a.	12.69	n.a.	62.43	n.a.
	Bond market	n.a.	39.56	n.a.	52.60	n.a.	8.13
	Country	0.14	9.17	0.01	4.32	0.11	4.13
	Idiosyncratic	0.93	23.92	7.81	6.21	0.78	10.04
US	**Non-contagion**	**47.48**	**93.67**	**55.11**	**49.47**	**88.10**	**39.08**
	Common	14.10	37.01	1.66	5.54	2.71	14.08
	Equity market	28.92	n.a.	52.41	n.a.	25.02	n.a.
	Bond market	n.a.	23.60	n.a.	20.15	n.a.	1.47
	Country	0.16	5.68	0.01	1.01	2.48	0.11
	Idiosyncratic	4.29	27.38	0.72	22.75	57.50	23.42

Note: The volatility decomposition is presented as a percentage of total volatility. n.a. denotes not applicable.

A.4 Statistical Significance of Contagion and Structural Breaks: Models with Alternative European Crisis Sources

	DOF	Model with Greece	Model with Italy
Contagion			
Equity market	5	23.015 (0.000)	1932.147 (0.000)
Bond market	5	5336.029 (0.000)	573.435 (0.000)
Idio. EU equity	9	513.493 (0.000)	1134.012 (0.000)
Idio. US equity	9	2820.451 (0.000)	263.676 (0.000)
Idio. EU bond	9	855.986 (0.000)	541.546 (0.000)
Idio. US bond	9	12369.210 (0.000)	265.778 (0.000)
Joint contagion	46	24985.417 (0.000)	1285.140 (0.000)
Structural breaks			
Equity market	5	298.379 (0.000)	598.458 (0.000)
Bond market	5	2439.534 (0.000)	711.517 (0.000)
Idio. EU equity	1	141.953 (0.000)	86.172 (0.000)
Idio. US equity	1	4.540 (0.033)	0.205 (0.651)
Idio. EU bond	1	9.789 (0.002)	5.337 (0.021)
Idio. US bond	1	205.202 (0.000)	0.551 (0.458)
Joint structural breaks	14	4139.297 (0.000)	1932.147 (0.000)

Note: Test statistics are based on the Wald test. p-values are in parentheses.

Appendix B

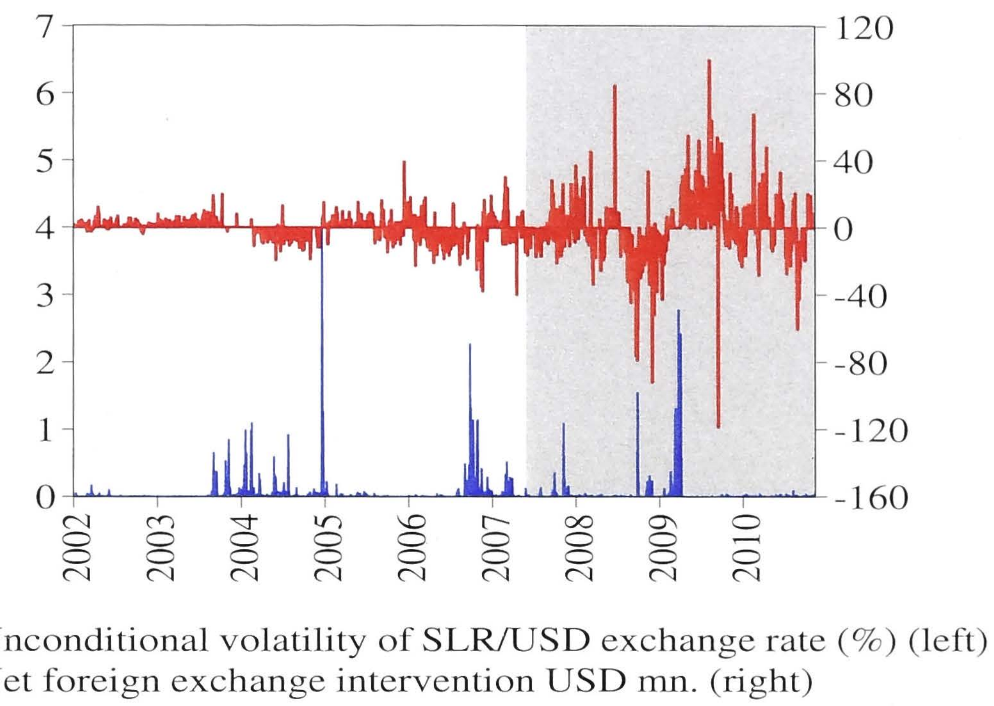
Chapter 4 Appendices

B.1 Descriptive Statistics

Variable	Max	Min	Mean	Std. dev.	No of obs.
Total sample					
Exchange rate returns	1.25	-2.04	0.01	0.17	2171
Gvt. bond spread (bps)	1423.90	229.01	787.47	334.42	2172
Int.rate differential (%)	19.30	4.51	9.76	4.11	2172
Non-crisis period					
Exchange rate returns	1.15	-2.04	-0.01	0.19	1324
Gvt bond spread (bps)	1023.0	229.01	621.79	243.71	1325
Int.rate differential (%)	19.30	4.51	8.59	3.79	1325
Crisis period					
Exchange rate returns	1.25	-1.67	4.9×10^{-4}	0.16	847
Gvt bond spread (bps)	1423.90	382.04	1046.15	289.79	848
Int.rate differential (%)	18.20	6.70	11.58	3.94	848

Note: The exchange rate is expressed in terms of US dollars. The total sample is from January 1, 2002 to December 31, 2010. The non-crisis period is from January 1, 2002 to June 29, 2007, and the crisis period is from July 2, 2007 to December 31, 2010.

B.2 Unconditional Volatility of the Exchange Rate Against the US dollar and Net Foreign Exchange Intervention (USD mn).



Note: Unconditional volatility is measured by the square of the percentage change in the daily log exchange rate. The shaded area indicates the crisis period from July 02, 2007 to December 31, 2010 (Source: Central Bank of Sri Lanka).

B.3 Unit Root Tests

	ADF test statistics[(a)]	
	level	first difference
Exchange rate returns	-11.12 ***	-
Int. rate differential	-0.89	-9.90 ***
Government bond spread	-1.46	-11.91 ***
Net intervention (US$m)	-6.62 ***	-
Purchases (US$m)	-6.73 ***	-
Sale (US$m)	-7.28 ***	-

Note: [(a)] denotes the Augmented Dickey-Fuller test with a trend term and a maximum number of 15 lags selected according to the BIC. *** indicates that the null hypothesis of a unit root is rejected at the 1 per cent level.

B.4 Correlation between Sri Lankan Rupee Returns and Foreign Exchange Intervention

	SLR returns	One-day lagged SLR returns
SLR returns	1.000	0.302
One-day lagged SLR returns	0.302	1.000
Net purchases of US dollars	-0.170	-0.126
Purchase of US dollars	-0.168	-0.138
Sale of US dollars	-0.094	-0.058

Note: Correlation between Sri Lankan Rupee (SLR) Returns and Foreign Exchange Intervention During the Non-crisis Period: January 01, 2002 to June 29, 2007.

	SLR returns	One-day lagged SLR returns
SLR returns	1.000	0.458
One-day lagged SLR returns	0.458	1.000
Net purchases of US dollars	-0.181	-0.125
Purchase of US dollars	-0.106	-0.105
Sale of US dollars	-0.173	-0.086

Note: Correlation between Sri Lankan Rupee (SLR) Returns and Foreign Exchange Intervention During the Crisis Period: July 01, 2007 to December 31, 2010.

Bibliography

Abenoja, Z. (2003). Foreign Exchange Market Intervention: A Short Review of Transmission Channels and Practices. *Bangko Sentral Review* 5(2), 1–25.

Adler, G. and C. E. Tovar (2011). *Foreign Exchange Intervention: A Shield against Appreciation Winds?* IMF Working Paper No. 11/165.

Adrian, T. and H. Shin (2011). Financial Intermediary Balance Sheet Management. *Annual Review of Financial Economics* 3(1), 289–307.

Aksentic, M., C. Jumashukurov, K. Kuzovkov, G. Ludviksson, and F. Zinoecker (2008). Icelandic Financial Service Cluster. Technical report. Harvard Business School, http://www.isc.hbs.edu/pdf/Student_Projects/Iceland_Financial_Services_2008.pdf (02/06/2009).

Allen, F. and D. Gale (2000). Financial Contagion. *Journal of Political Economy* 108(1), 1–33.

Almekinders, G. J. and S. C. W. Eijffinger (1996). A Friction Model of Daily Bundesbank and Federal Reserve Intervention. *Journal of Banking and Finance* 20(8), 1365–1380.

Anand, R., D. Ding, and S. J. Peiris (2011). *Toward Inflation Targeting in Sri Lanka.* IMF Working Paper No. 11/81.

Angeletos, G. M. and I. Werning (2006). Crises and Prices: Information Aggregation, Multiplicity, and Volatility. *The American Economic Review* 96(5), 1720–1736.

Arieff, A. (2010). *Global Economic Crisis: Impact on Sub-Saharan Africa and Global Policy Responses.* Diane Publishing, Pennsylvania.

Aruman, S. (2003). *The Effectiveness of Foreign Exchange Intervention in Australia: A Factor Model Approach with GARCH Specifications.* Queensland University of Technology School of Economics and Finance Discussion Paper No. 135.

Bae, K., G. Karolyi, and R. Stulz (2003). A New Approach to Measuring Financial Contagion. *Review of Financial Studies* 16(3), 717–763.

Baillie, R. T. and T. Bollerslev (1989). Common Stochastic Trends in a System of Exchange Rates. *Journal of Finance* 44(1), 167–181.

Behera, H., V. Narasimhan, and K. N. Murty (2008). Relationship between Exchange Rate Volatility and Central Bank Intervention. *South Asia Economic Journal* 9(1), 69–84.

Beine, M., A. Bénassy-Quéré, and C. Lecourt (2002). Central Bank Intervention and Foreign Exchange Rates: New Evidence from FIGARCH Estimations. *Journal of International Money and Finance* 21(1), 115–144.

Bekaert, G., M. Ehrmann, M. Fratzscher, and A. J. Mehl (2011). *Global Crises and Equity Market Contagion.* NBER Working Paper No. 17121.

Bekaert, G., C. R. Harvey, and A. Ng (2005). Market Integration and Contagion. *Journal of Business* 78(1), 39–69.

Bekaert, G. and R. J. Hodrick (1992). Characterizing Predictable Components in Excess Returns on Equity and Foreign Exchange Markets. *Journal of Finance* 47(2), 467–509.

Bikhchandani, S. and S. Sharma (2000). Herd behavior in Financial Markets. *IMF Staff Papers* 47(3), 279–310.

Billio, M. and M. Caporin (2010). Market Linkages, Variance Spillovers, and Correlation Stability: Empirical Evidence of Financial Contagion. *Computational Statistics and Data Analysis* 54(11), 2443–2458.

BIS (2005). *Foreign Exchange Market Intervention in Emerging Markets: Motives, Techniques and Implications.* Bank for International Settlements Paper No. 24.

Bofinger, P. (2001). *Monetary Policy: Goals, Institutions, Strategies, and Instruments.* Oxford University Press, Oxford.

Bollerslev, T. (1986). Generalized Autoregressive Conditional Heteroskedasticity. *Journal of Econometrics* 31(3), 307–327.

Bonser-Neal, C. and G. Tanner (1996). Central Bank Intervention and the Volatility of Foreign Exchange Rates: Evidence from the Options Market. *Journal of International Money and Finance* 15(6), 853–878.

Bordo, M. (2008). *An Historical Perspective on the Crisis of 2007-2008.* NBER Working Papers No.14569.

Boyer, B., T. Kumagai, and K. Yuan (2006). How Do Crises Spread? Evidence From Accessible And Inaccessible Stock Indices. *The journal of finance* 61(2), 957–1003.

Brunnermeier, M. K. and L. H. Pedersen (2009). Market Liquidity and Funding Liquidity. *Review of Financial Studies* 22(6), 2201–2238.

Calvo, G. A. and E. G. Mendoza (2000). Rational Contagion and the Globalization of Securities Markets. *Journal of International Economics* 51(1), 79–113.

Campbell, J., A. Lo, and A. MacKinlay (1997). *The Econometrics Of Financial Markets*. Princeton University Press, New Jersey.

Caramazza, F., L. A. Ricci, and R. Salgado (2000). *Trade and Financial Contagion in Currency Crises*. IMF Working Paper No. 00/55.

Carlsson, H. and E. Van Damme (1993). Global Games and Equilibrium Selection. *Econometrica* 61(5), 989–1018.

Chang, R. and A. Velasco (2001). A Model of Financial Crises in Emerging Markets. *The Quarterly Journal of Economics* 116(2), 489–517.

Chiang, S., Y. Lee, H. Su, and Y. Tzou (2010). Efficiency Tests of Foreign Exchange Markets for Four Asian Countries. *Research in International Business and Finance* 24(3), 284–294.

Cipriani, M. and A. Guarino (2005). Herd Behavior in a Laboratory Financial Market. *American Economic Review* 95(5), 1427–1443.

Collier, P. (2010). *The Effects of the Economic Crisis on the Poorest Developing Countries*. A paper prepared for Legatum Instutute Global Economic Symposium, http://www.global-economic-symposium.org/solutions/the-global-polity/sustainability-and-global-governance/strategyperspectivefolder/the-effects-of-the-economic-crisis-on-the-poorest-developing-countries (16/05/2012).

Crotty, J. (2009). Structural Causes of the Global Financial Crisis: A Critical Assessment of the "New Financial Architecture". *Cambridge Journal of Economics* 33(4), 563–580.

de Bandt, O., K. Barhoumi, and C. Bruneau (2010). The International Transmission of House Price Shocks. In O. de Bandt, T. Knetsch, J. Peñalosa, and F. Zollino (Eds.), *Housing Markets in Europe: A Macroeconomic Perspective*, pp. 129–160. Springer Verlag, Berlin.

Diebold, F. X. and M. Nerlove (1989). The Dynamics of Exchange Rate Volatility: A Multivariate Latent Factor ARCH Model. *Journal of Applied Econometrics* 4(1), 1–21.

Diebold, F. X. and K. Yilmaz (2012). Better to Give than to Receive: Predictive Directional Measurement of Volatility Spillovers. *International Journal of Forecasting* 28(1), 57 – 66.

Disyatat, P. and G. Galati (2007). The Effectiveness of Foreign Exchange Intervention in Emerging Market Countries: Evidence from the Czech Koruna. *Journal of International Money and Finance* 26(3), 383–402.

Domaç, I. and A. Mendoza (2004). *Is There Room for Foreign Exchange Interventions under an Inflation Targeting Framework? Evidence from Mexico and Turkey*. World Bank Policy Research Working Paper No. 3288.

Dominguez, K. M. (1998). Central Bank Intervention and Exchange Rate Volatility. *Journal of International Money and Finance* 17(1), 161–190.

Dominguez, K. M. (2010). International Reserves and Underdeveloped Capital Markets. In L. Reichlin and K. West (Eds.), *NBER International Seminar on Macroeconomics 2009*, pp. 193–221. University of Chicago Press, Chicago.

Dominguez, K. M. and J. A. Frankel (1993). Does Foreign Exchange Intervention Matter? The Portfolio Effect. *American Economic Review* 83(5), 1356–1369.

Dominguez, K. M., Y. Hashimoto, and T. Ito (2011). *International Reserves and the Global Financial Crisis.* NBER Working Paper No. 17362.

Dornbusch, R., Y. C. Park, and S. Claessens (2001). Contagion: How It Spreads and How It Can Be Stopped? In S. Claessens and K. Forbes (Eds.), *International Financial Contagion*, pp. 19–42. Kluwer Academic Publishers, New York.

Dungey, M. (1999). Decomposing Exchange Rate Volatility around the Pacific Rim. *Journal of Asian Economics* 10(4), 525–535.

Dungey, M. (2008). The Tsunami: Measures of Contagion in the 2007-2008 Credit Crunch. In *CESifo Forum*, Volume 9, pp. 33–43. Ifo Institute for Economic Research, University of Munich.

Dungey, M., R. Fry, B. Gonzalez-Hermosillo, and V. Martin (2005). Empirical Modelling of Contagion: A Review of Methodologies. *Quantitative Finance* 5(1), 9–24.

Dungey, M., R. Fry, B. González-Hermosillo, and V. L. Martin (2011). *Transmission of Financial Crises and Contagion: A Latent Factor Approach.* Oxford University Press, Oxford.

Dungey, M., R. Fry, and V. L. Martin (2006). Correlation, Contagion, and Asian Evidence. *Asian Economic Papers* 5(2), 32–72.

Dungey, M. and V. L. Martin (2004). A Multifactor Model of Exchange Rates with Unanticipated Shocks: Measuring Contagion in the East Asian Currency Crisis. *Journal of Emerging Market Finance* 3(3), 305–330.

Dungey, M. and V. L. Martin (2007). Unravelling Financial Market Linkages During Crises. *Journal of Applied Econometrics* 22(1), 89–119.

Edison, H. J. (1993). *The Effectiveness of Central-Bank Intervention: A Survey of the Literature after 1982.* Princeton Studies in International Economics, Special Paper Series No. 18.

Edwards, S. and J. Frankel (2002). Introduction to Preventing Currency Crises in Emerging Markets. *NBER Chapters*, 1–20.

Ehrmann, M., M. Fratzscher, and R. Rigobon (2011). Stocks, Bonds, Money Markets and Exchange Rates: Measuring International Financial Transmission. *Journal of Applied Econometrics* 26(6), 948–974.

Eichengreen, B., A. Rose, and C. Wyplosz (1996). Contagious Currency Crises: First Tests. *Scandinavian Journal of Economics* 98(4), 463–484.

Engle, R. F. (1982). Autoregressive Conditional Heteroscedasticity with Estimates of the Variance of United Kingdom Inflation. *Econometrica* 50(4), 987–1007.

Engle, R. F. and T. Bollerslev (1986). Modelling the Persistence of Conditional Variances. *Econometric Reviews* 5(1), 1–50.

Engle, R. F., T. Ito, and W. L. Lin (1990). Meteor Showers or Heat Waves? Heteroskedastic Intra-Daily Volatility in the Foreign Exchange Market. *Econometrica* 58(3), 525–542.

Fama, E. F. (1970). Efficient Capital Markets: A Review of Theory and Empirical Work. *Journal of Finance* 25(2), 383–417.

Fatum, R. (2003). Is Sterilised Foreign Exchange Intervention Effective after All? An Event Study Approach. *Economic Journal* 113(487), 390–411.

Fatum, R. and M. Hutchison (2006). Effectiveness of Official Daily Foreign Exchange Market Intervention Operations in Japan. *Journal of International Money and Finance* 25(2), 199–219.

Favero, C. and F. Giavazzi (2002). Is the International Propagation of Financial Shocks Non-linear?: Evidence from the ERM. *Journal of International Economics* 57(1), 231–246.

Fleming, J., C. Kirby, and B. Ostdiek (1998). Information and Volatility Linkages in the Stock, Bond, and Money Markets. *Journal of Financial Economics* 49(1), 111–137.

Forbes, K. J. and R. Rigobon (2002). No Contagion, Only Interdependence: Measuring Stock Market Comovements. *The Journal of Finance* 57(5), 2223–2261.

Gai, P., A. Hadane, and S. Kapadia (2011). Complexity, Concentration and Contagion. *Journal of Monetary Economics* 58(5), 453–470.

Gai, P. and K. Trivedi (2009). Funding Externalities, Asset prices and Investors' 'Search for Yield'. *Bulletin of Economic Research* 61(1), 73–82.

Galati, G., W. Melick, and M. Micu (2005). Foreign Exchange Market Intervention And Expectations: The Yen/Dollar Exchange Rate. *Journal of International Money and Finance* 24(6), 982–1011.

Gale, D. (1996). What Have We Learned from Social Learning? *European Economic Review* 40(3), 617–628.

Gallo, G. and E. Otranto (2008). Volatility Spillovers, Interdependence and Comovements: A Markov Switching Approach. *Computational Statistics and Data Analysis* 52(6), 3011–3026.

Gärtner, M. (1987). Intervention Policy under Floating Exchange Rates: An Analysis of the Swiss Case. *Economica* 54(216), 439–453.

Geanakoplos, J. (2010). Solving the Present Crisis and Managing the Leverage Cycle. *Economic Policy Review* 16(1), 101–131.

Goldstein, I. (2005). Strategic Complementarities and the Twin Crises. *The Economic Journal* 115(April), 368–390.

Goldstein, I. and A. Pauzner (2005). Demand Deposit Contracts and the Probability of Bank Runs. *The Journal of Finance* 60(3), 1293–1327.

Gorton, G. B. and A. Metrick (2009). *Haircuts*. NBER Working Paper No. 15273.

Goyal, A. and S. Arora (2010). *The Indian Exchange Rate and Rentral Bank Action: A GARCH Analysis*. Indira Gandhi Institute of Development Research Working Paper No. 10/009.

Green, D., R. King, and M. Miller-Dawkins (2010). *The Global Economic Crisis and Developing Countries: Impact and Response*. International Research Report, Oxfam International, New York. http://www.oxfam.org.uk/resources/policy/economic_crisis/downloads/rr_gec_and_developing_countries_full_en_260510. pdf (16/05/2012).

Guimarães, R. F. and C. Karacadag (2004). *The Empirics of Foreign Exchange Intervention in Emerging Market Countries: The Cases of Mexico and Turkey*. IMF Working Paper No. 04/123.

Hamilton, J. D. (1994). Time Series Analysis.

Hartmann, P., S. Straetmans, and C. G. Vries (2004). Asset Market Linkages in Crisis Periods. *Review of Economics and Statistics* 86(1), 313–326.

Hellwig, C., A. Mukherji, and A. Tsyvinski (2006). Self-fulfilling Currency Crises: The Role of Interest Rates. *American Economic Review* 96(5), 1769–1787.

Hentschel, L. (1995). All in the Family: Nesting Symmetric and Asymmetric GARCH Models. *Journal of Financial Economics* 39(1), 71–104.

Herrera, A. and P. Ozbay (2005). *A Dynamic Model of Central Bank Intervention*. Central Bank of the Republic of Turkey Working Paper No. 05/01.

Hillebrand, E. and G. Schnabl (2003). *The Effects of Japanese Foreign Exchange Intervention: GARCH Estimation and Change Point Detection*. Japan Bank for International Corporation Institute Working Paper No. 6.

Hodson, D. and L. Quaglia (2009). European Perspectives on the Global Financial Crisis: Introduction. *Journal of Common Market Studies* 47(5), 939–953.

Hoshikawa, T. (2008). The Effect of Intervention Frequency on the Foreign Exchange Market: The Japanese Experience. *Journal of International Money and Finance* 27(4), 547–559.

Hung, J. H. (1997). Intervention Strategies and Exchange Rate Volatility: A Noise Trading Perspective. *Journal of International Money and Finance* 16(5), 779–793.

Hussain, F. and A. Jalil (2007). *Effectiveness of Foreign Exchange Intervention: Evidence from Pakistan.* State Bank of Pakistan Research Bulletin No. 3(2).

Ito, T. and Y. Hashimoto (2005). High-Frequency Contagion between Exchange Rates and Stock Prices during the Asian Currency Crisis. In M. Dungey and D. Tambakis (Eds.), *Identifying International Financial Contagion: Progress and Challenges*, pp. 111–149. Oxford University Press, Oxford.

Ivashina, V. and D. Scharfstein (2010). Bank Lending During the Financial Crisis of 2008. *Journal of Financial Economics* 97(3), 319–338.

Kamil, H. (2008). *Is Central Bank Intervention Effective under Inflation Targeting Regimes? The Case of Colombia.* IMF Working Paper No. 08/88.

Kim, S., F. Moshirian, and E. Wu (2006). Evolution of International Stock and Bond Market Integration: Influence of the European Monetary Union. *Journal of Banking and Finance* 30(5), 1507–1534.

Kim, S. J. and J. Sheen (2002). The Determinants of Foreign Exchange Intervention by Central Banks: Evidence from Australia. *Journal of International Money and Finance* 21(5), 619–649.

King, M. A. and S. Wadhwani (1990). Transmission of Volatility between Stock Markets. *Review of Financial Studies* 3(1), 5–33.

Kiyotaki, N. and J. Moore (1997). Credit Cycles. *Journal of Political Economy* 105(2), 211–248.

Kleimeier, S., T. Lehnert, and W. Verschoor (2008). Measuring Financial Contagion using Time-Aligned Data: The Importance of the Speed of Transmission of Shocks. *Oxford Bulletin of Economics and Statistics* 70(4), 493–508.

Kodres, L. E. and M. Pritsker (2002). A Rational Expectations Model of Financial Contagion. *The Journal of Finance* 57(2), 769–799.

Kyle, A. S. and W. Xiong (2001). Contagion as a Wealth Effect. *The Journal of Finance* 56(4), 1401–1440.

Lane, P. R. and G. M. Milesi-Ferretti (2010). The cross-country incidence of the global crisis. *IMF Economic Review* 59(1), 77–110.

Longstaff, F. A. (2010). The Subprime Credit Crisis and Contagion in Financial Markets. *Journal of Financial Economics* 97(3), 436–450.

Mahieu, R. and P. Schotman (1994). Neglected Common Factors in Exchange Rate Volatility. *Journal of Empirical Finance* 1(3-4), 279–311.

Malkiel, B. (2003). The Efficient Market Hypothesis and Its Critics. *The Journal of Economic Perspectives* 17(1), 59–82.

Malkiel, B. (2005). Reflections on the Efficient Market Hypothesis: 30 Years Later. *Financial Review* 40(1), 1–9.

Mandeng, O. (2003). *Central Bank Foreign Exchange Market Intervention and Option Contract Specification: The Case of Colombia.* IMF Working Paper No. 03/135.

Masson, P. (1999a). Contagion: Macroeconomic Models with Multiple Equilibria. *Journal of International Money and Finance* 18(4), 587–602.

Masson, P. (1999b). Contagion: Monsoonal Effects, Spillovers, and Jumps between Multiple Equilibria. In P. R. Agnor, M. Miller, D. Vines, and A. A. Weber (Eds.), *The Asian Financial Crisis: Causes, Contagion and Consequences*, Volume 18, pp. 265–280. Cambridge University Press, Cambridge.

McKenzie, M. (2002). The Economics of Exchange Rate Volatility Asymmetry. *International Journal of Finance and Economics* 7(3), 247–260.

Metiu, N. (2012). Sovereign Risk Contagion in the Eurozone. *Economics Letters* 117(1), 35–38.

Mitra, S. (2011). A Review of Volatility and Option Pricing. *International Journal of Financial Markets and Derivatives* 2(3), 149–179.

Morris, S. and H. S. Shin (1998). Unique Equilibrium in a Model of Self-fulfilling Currency Attacks. *American Economic Review* 88(3), 587–597.

Morris, S. and H. S. Shin (2001). Rethinking Multiple Equilibria in Macroeconomic Modeling. *NBER Macroeconomics Annual 2000*, 15, 139–182.

Morris, S. and H. S. Shin (2004). LiquidityBlack Holes. *Review of Finance* 8(1), 1–18.

Morris, S. and H. S. Shin (2006). Catalytic Finance: When Does it Work? *Journal of international Economics* 70(1), 161–177.

Mulder, C. and R. Perrelli (2001). *Foreign Currency Credit Ratings for Emerging Market Economies.* IMF Working Paper No. 01/191.

Nelson, D. (1991). Conditional Heteroskedasticity in Asset Returns: A New Approach. *Econometrica* 59(2), 347–370.

Newey, W. K. and K. D. West (1987). A Simple, Positive Semi-definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix. *Econometrica* 55(3), 703–708.

Obstfeld, M. (1982). Can We Sterilize? Theory and Evidence. *American Economic Review* 72(2), 45–50.

Pattanaik, S. and S. Sahoo (2001). *The Effectiveness of Intervention in India: An Empirical Assessment.* Reserve Bank of India Occasional Paper No. 22.

Pericoli, M. and M. Sbracia (2003). A Primer on Financial Contagion. *Journal of Economic Surveys* 17(4), 571–608.

Pesaran, M. and A. Pick (2007). Econometric Issues in the Analysis of Contagion. *Journal of Economic Dynamics and Control* 31(4), 1245–1277.

Plantin, G. and H. S. Shin (2010). *Carry Trades and Speculative Dynamics.* Working Paper, http://www.princeton.edu/ hsshin/working.htm (10/09/2010).

Pontines, V. and R. S. Rajan (2011). Foreign Exchange Market Intervention and Reserve Accumulation in Emerging Asia: Is there Evidence of Fear of Appreciation? *Economics Letters* 111(3), 252–255.

Poon, S. H. and C. W. J. Granger (2003). Forecasting Volatility in Financial Markets: A Review. *Journal of Economic Literature* 41(2), 478–539.

Reitz, S. and M. P. Taylor (2008). The Coordination Channel of Foreign Echange Intervention: A Nonlinear Microstructural Analysis. *European Economic Review* 52(1), 55–76.

Reyes, M. (2001). Asymmetric Volatility Spillover in the Tokyo Stock Exchange. *Journal of Economics and Finance* 25(2), 206–213.

Sarno, L. and M. P. Taylor (2001). Official Intervention in the Foreign Exchange Market: Is it Effective and, if so, How Does it Work? *Journal of Economic Literature* 39(3), 839–868.

Schwert, G. W. (2011). Stock Volatility During the Recent Financial Crisis. *European Financial Management* 17(5), 789–805.

Scott, L. O. (1991). Financial Market Volatility: A Survey. *IMF Staff Papers* 38(3), 582–625.

Shah, M. K. A., Z. Hyder, and M. K. Pervaiz (2009). Central Bank Intervention and Exchange Rate Volatility in Pakistan: An Analysis using GARCH-X Model. *Applied Financial Economics* 19(18), 1497–1508.

Sharpe, W. F. (1964). Capital Asset Prices: A Theory of Market Equilibrium Under Conditions of Risk. *Journal of Finance* 19(3), 425–442.

Shin, H. S. (2005). Liquidity and Twin Crises. *Economic Notes* 34(3), 257–277.

Simwaka, K. (2011). Official Intervention in the Foreign Exchange Market in Malawi: Evidence from GARCH and Equilibrium Exchange Rate Methods. *Journal of Economics and International Finance* 3(7), 428–443.

Smith, L. and P. Sørensen (2000). Pathological Outcomes of Observational Learning. *Econometrica* 68(2), 371–398.

So, M. K. P., K. Lam, and W. K. Li (1997). An Empirical Study of Volatility in Seven Southeast Asian Stock Markets Using ARV Models. *Journal of Business Finance and Accounting* 24(2), 261–276.

Suardi, S. (2008). Central Bank Intervention, Threshold Effects and Asymmetric Volatility: Evidence from the Japanese Yen-US Dollar Foreign Exchange Market. *Economic Modelling* 25(4), 628–642.

Szakmary, A. C. and I. Mathur (1997). Central Bank Intervention and Trading Rule Profits in Foreign Exchange Markets. *Journal of International Money and Finance* 16(4), 513–535.

Tuna, G. (2011). The Effectiveness of Central Bank Intervention: Evidence from Turkey. *Applied Economics* 43(14), 1801–1815.

Van Royen, A. (2002). Financial Contagion and International Portfolio Flows. *Financial Analysts Journal* 58(1), 35–49.

Xiong, W. (2001). Convergence Trading with Wealth Effects: an Amplification Mechanism in Financial Markets. *Journal of Financial Economics* 62(2), 247–292.

Yap, J., C. Reyes, and J. Cuenca (2009). *Impact of the Global Financial and Economic Crisis on the Philippines.* A Paper Prepared for the United Nations Development Programme, http://www.unicef.org/socialpolicy/files/Impact_of_the_Global_Finanical_and_Economic_Crisis_on_the_Philippines.pdf (16/05/2012).